Interpretation of centrifuge data using local saturation.

M. Fleury, R. Lenormand and F. Deflandre.

Institut Français du Pétrole.

Abstract

We report multi-speed centrifuge experiments in which local saturation were measured while spinning. The local saturation are deduced from the transit time of ultrasonic waves travelling through the sample. The precision of the measurements depends on empirical corrections applied on the data to take into account pressure and stress effects on the sample.

Local measurements permitted the observation of different processes, for instance a quasi-spontaneous drainage at low speed of rotation and fluid redistribution at the end of drainage before forced imbibition.

The measured saturation profiles are consistent with the assumptions of zero capillary pressure at the outflow face. We did not observe any contradiction between the direct determination of the Pc curves and the computed ones. However, the direct determinations are not perfectly superimposed, due to errors of measurements and small heterogeneities.

Local saturation measurements in multi-speed centrifuge experiments do not improve in practice the determination of relative permeability curves due to the high sensitivity of the computation to the values of capillary pressure.

Introduction

The centrifuge technique is the fastest and simplest method to obtain capillary pressure (Pc) curves and a considerable amount of work has been devoted to this technique. Yet, it is still a subject of controversy because the Pc or Kr are not directly measured but derived from a mathematical calculation. So far, improvements have mainly focused on the measurement of production and the calculation of the Pc curve from these data. The difficulty induced by the non-uniform saturation profile can also be overcome by using local saturation measurements while centrifuging.

Local saturation measurements along the sample can provide a direct determination of the Pc curve since the pressure field is directly linked to the rotation speed (assuming fluid continuity in the sample). Local measurement can also provide, in principle, a better determination of the relative permeability (Kr) curves. The first use of local saturation measurements while centrifuging to obtain a drainage Pc curve has been reported by Forbes *et al.* (1992). Chardaire *et al.* (1992) used the same ultrasonic technique to determine the relative permeability curves during drainage of a Berea sandstone. In this paper, we report (i) significant improvement of the ultrasonic technique in the centrifugation case (ii) direct determination of drainage and imbibition Pc curves for sample of different wettability (iii) a comparison between Kr curves computed from production and local saturation.

For clarity, we define the terminology used in this paper:

- Drainage: decreasing water saturation ,
- Imbibition: increasing water saturation ,

- Forced imbibition: sample centrifuged in water.
- Spontaneous drainage or imbibition: no pressure difference between faces is applied (no rotation)
- Quasi-spontaneous drainage or imbibition: sample centrifuged at low rotation speed. The imposed pressure gradient is assumed to be negligible.

Experimental set-up

The experimental set-up is an improved version of the one used in Forbes *et al.* (1992). The number of local measurements has been increased from 3 to 5 (table 1, R1 to R5) for a better resolution of the saturation profiles. The transducer supports were modified for better mechanical and electrical behaviour. Two pairs of different core holders were built for drainage and forced imbibition. Both were designed for cylindrical samples 7 cm in length and 2.5 cm in diameter. The end piece support placed at the outer face (R_{max}) is oil wet, as recommended by O' Meara *et al.*, (1988). There is no support at the inner face (R_{min}). For both core holders, the water or oil production collected in a transparent graduated tube can be read while centrifuging using a stroboscope with an accuracy of ±0.1 cc.

The fluids used were brine (50g of NaCl per litre, density 1.036) and a mixture of refined oil, Soltrol and Albelf (density 0.822). The oil mixture has a viscosity of 15 cP in order to increase the imbibition time scale (see Results section). The oil/brine interfacial tension is 40 mN/m. The initial brine saturation was performed very carefully because small traces of air (as small as 0.5 %PV) can generate important artefacts in the ultrasonic measurements and lead to wrong conclusions about the state of saturation after displacement. The samples were first saturated under vacuum and then put under a pressure of 100 Bar during 1/2 hour. This method was particularly useful to remove the traces of air in samples not strongly water wet.

Sample:	Porosity (%)	K (mD)	Rmax (cm)	Rmin(cm) =Rmax-L	R1 (cm)	R2 (cm)	R3 (cm)	R4 (cm)	R5 (cm)
S1 drainage	24.3	600	15.55	8.55	9.45	10.85	12.25	13.65	15.05
S2 drainage	23.6	250	15.55	9.25	/	10.85	12.25	13.65	15.05
imbibition			23.4	17.1	/	18.5	19.9	21.3	22.7
S3 imbibition	22.3	13	23.4	18.95	/	/	20.3	21.5	22.7

Table 1: characteristics of the experimental set-up. R1 to R5 are the radii of rotation of the local measurements.

Local saturation measurements

A background on the ultrasonic technique can be found in Deflandre and Lenormand (1993). We discuss here only the specific problems when applying this technique while centrifuging. The measured quantity is the transit time of compressional waves between a pair of piezo-electric ceramics (at a frequency of 350 kHz). From the size of these ceramics, we can consider that a 3mm thick slice of the porous sample is analysed. Saturation are derived from ultrasonic measurements by using a calibration curve, after correction of temperature and rotation effects.

Temperature and rotation effects

The effect of temperature is a minor source of error in our experiments. Due to the temperature regulation of the centrifuge, there is a fluctuation of ±3.5 °C with a period of about 15 mn. Thus, the ultrasonic signals contain fluctuations with a similar period. The variation of temperature from low to high speed of rotation are checked using the twin core holder in which a companion plug saturated with brine is centrifuged under brine. If necessary, the signals from

the core holder in which the drainage or the imbibition experiment is performed can be corrected.

The effect of rotation, a combination of pressure on the liquids and stress on the sample, is a dominant source of error. Before calibration and only for the drainage experiments, we applied a correction of the form:

(1) $$t_c = \alpha(S_o, R)\,\omega^2$$

where α is a coefficient depending on the saturation and the radius of rotation (R1 to R5). The proportionality to ω^2 has been observed when centrifuging a sample 100% saturated with brine immersed in brine (hence, there is no saturation change). There is also a dependence with the radius of rotation but an analytical relation has not been found. In practice, the coefficient α is estimated at S_o=1-Swi and at each location at the end of the experiment when the centrifuge is stopped. At that moment, the saturation at each location of measurement is minimum or equal to the irreducible water saturation Swi. These corrections are important above 1500 rpm and for channel 4 and 5 only (largest radii). On channel 5, the correction can be as large as 100%.

For the imbibition experiments, the radii of rotation are larger (table 1) and the rotation effect is important on all channels above 1500 rpm. However, the empirical correction described above did not lead to consistent results, probably because the saturation dependence is not well described and cannot be estimated. Thus, no correction was applied for data below 1500 rpm and data above 1500 rpm were not interpreted.

Calibration

From the Biot-Gasmann theory and using some assumptions about the average properties of the two fluids in the porous medium (Bacri *et al.*, 1986), the oil saturation S_o was determined using a second order polynomial of the form:

(2) $$S_o = a\,\eta^2 + b\eta \quad \text{where} \quad \eta = \frac{t - t_0 - t_c}{t_0}$$

From the comparison of ultrasonic with CT scan measurements, Forbes *et al.* (1993) showed clearly that a relation of the form (2) is valid with a very weak non linearity. The average saturation $\overline{S_o}$ is calculated using a trapezoidal integration of the profiles at equilibrium:

(3) $$\overline{S_o} = \sum_{i=1}^{7} (S_i + S_{i-1})\left(\frac{x_i - x_{i-1}}{2L}\right)$$

where S_i is the saturation at a location x_i. S_1 is the saturation at $R=R_{min}$ and S_7 at $R=R_{max}$. It is assumed that $S_1=S_2$ and $S_7=0$ for drainage and S_1=1-Swi; $S_7=S_6$ for imbibition. The coefficients a and b are calculated using all the average saturation data available at equilibrium: an over-determined system of two unknowns and n equations is solved, where n is the number of rotation steps (from 5 to 10). This calibration procedure tested on synthetic data generated less than 1 %PV error on the saturation.

The accuracy, expressed in terms of variation of transit time is estimated to ±15 ns. When the saturation varies from Sw=1 down to Swi (drainage case), the transit time variation ranges from 150 ns up to 500 ns depending on the nature of the sample (limestone or sandstone) and the fluids. Thus, we have a relative error ranging from 10% to 3%, respectively. In the latter case, if the brine saturation varies from 100 down to 20% PV, we will have an absolute error of about 4% PV. Note that the error generated by the large corrections made on channel 5 will affect the other channels because the data are calibrated using average saturation measurements; a shift or error of saturation at one location will be compensated by opposite shifts at the other locations.

Pc curves determinations

From the local saturation measurements, we deduce the capillary pressure curve at a location R by plotting the known capillary pressure at R and speed ω versus the saturation (averaged over 15 mn) at R obtained at the end of the step at speed ω. For drainage, $Pc=\Delta\rho/2\omega^2(R^2_{max}-R^2)$ with the assumption $Pc(R_{max})=0$, and for imbibition $Pc=\Delta\rho/2\omega^2(R^2_{min}-R^2)$ with the assumption $Pc(R_{min}=0)$.

From the production measurements, the capillary pressure curve was calculated using the Forbes' methods (1991). The latest version of the software includes the radial effects (Forbes, 1994) which are, however, negligible for our geometry (large radius of rotation and small sample diameter, table 1).

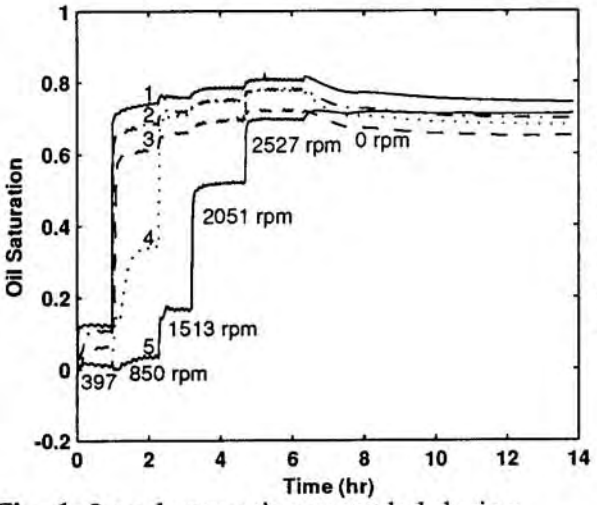

Fig. 1: Local saturation recorded during drainage of sample S1.

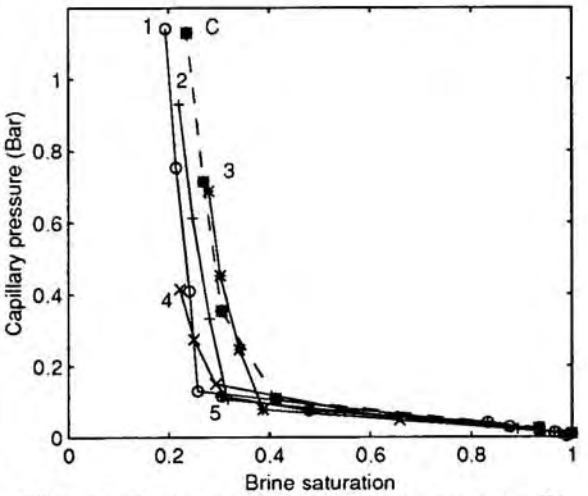

Fig. 2: Drainage Pc curves for sample S1. Direct determinations (1 to 5) and computed Pc curves (C).

Results: Capillary pressure curves

Experiments on three samples of different wettabilities are reported here. The local saturation measurements enable us to observe phenomena that cannot be inferred from the measurement of production alone, for example the fluid redistribution at the end of drainage when the centrifuge is stopped or the quasi-spontaneous drainage of a non strongly water wet sample.

Water wet sample S1

Drainage:

The data recorded during drainage are shown in fig. 1. The progressive invasion of oil is clearly observed. The stabilisation is faster at location 1 than at location 4 or 5 because of the difference in relative permeability. The five Pc curves deduced from the measurements are shown in fig. 2. Except for curve 3, there is a good agreement within the different determinations. For this experiment, the precision can be estimated to ±2% which, however, does not fully explain the difference between curve 3 and the others. The curve computed from the average saturation agree with the direct determinations, although the number of data available is small (5 data points). The difference in Swi is within the errors of measurements.

Fluid redistribution:

After the centrifuge has been stopped, the core holders were kept at constant temperature and the local saturation recorded (the sample has not been moved out). The average saturation being constant, a fluid redistribution is expected to yield a uniform capillary pressure along the

sample. The data recorded during fluid redistribution are shown in fig. 1 (data after 6 hr). We see a decrease of oil saturation on all channels but number 5 closest to the outlet face. These variations correspond to a displacement of water from the outlet face ('water foot') towards the inlet face with typical time scale of one hour. The non-uniform final saturation profile can be explained by the hysteresis of the capillary pressure curves. Baardsen *et al.* (1989) found similar results using CT scan. Cuiec *et al.* (1990) observed that spontaneous imbibition processes can be properly scaled by:

$$t_i = \frac{\mu_o L^2}{\sigma \sqrt{K}} \quad (4)$$

This equation results of Darcy's law applied to the displacement of oil at velocity L/t_i under the pressure gradient Pc/L, where the capillary pressure Pc is approximated by $\sigma\sqrt{K}$. For the present case, we found t_i= 0.6 hour in good agreement with the observations. This time scale was also valid for the spontaneous imbibition on this sample.

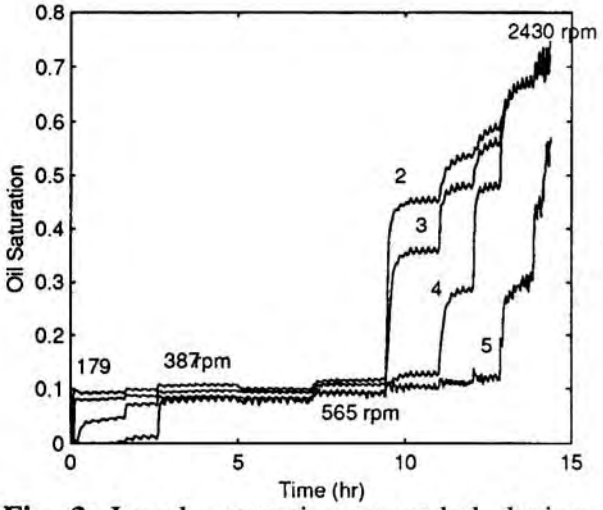

Fig. 3: Local saturation recorded during drainage of sample S2. The full sequence of rotation steps is: 179, 245, 387, 565, 836, 1023, 1246, 1777, 2097 and 2430 rpm.

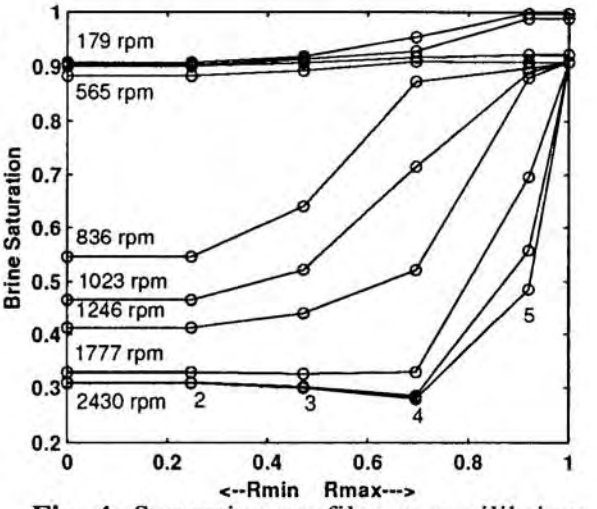

Fig. 4: Saturation profiles at equilibrium during drainage of sample S2. A quasi-spontaneous drainage is observed at low speed. The saturation at the faces (R_{min} and R_{max}) are not measured.

Intermediate wet sample S2

Drainage:

This reservoir sample was cleaned by flooding several pore volumes of methanol, toluene and methanol. This is a strong cleaning , which should yield a water wet sample (Cuiec, 1991). However, a quasi-spontaneous drainage was observed at low speed of rotation (fig. 3). When increasing the speed of rotation stepwise from 179 to 565 rpm, we saw a change of saturation at all locations and in particular at location 5, closest to the outlet face. This effect is due to the wettability of the sample. As a result, we obtain a nearly uniform profile in the sample (fig. 4). Above 565 rpm, the sample behaves like a water-wet sample: oil is penetrating gradually the sample from the inlet to the outlet face.

The Pc curves (fig. 5) reflect the wetting tendency of the sample. Pc values are close to zero down to a saturation of about 0.9. The air water porous plate measurements (PP in fig. 5), performed on a companion plug, cannot indicate that tendency. There is a general agreement between the computed and direct measurement of the Pc curves.

Forced imbibition:

Only the recordings below 1250 rpm were interpreted because of calibration problems. During forced imbibition, a variation of oil saturation can be observed at all locations (fig. 6)

but is larger at location 5 (closest to the inlet face). At 237 rpm, about 15 hours are needed to reach equilibrium. For the three last rotation steps (394, 681 and 1222 rpm), equilibrium was clearly not reached after 2 hours although most of the oil is produced. These equilibration time are much larger (an order of magnitude) than typical time scale inferred from (4) or observed during drainage. Although no microscopic analysis is available, long equilibration times would be consistent with the existence of thin films as described by Radke *et al.* (1992).

There is no disagreement between the computed and direct determination of the Pc curves (fig. 7). However, for the direct determinations, a higher saturation is obtained for a small radius of rotation, even at small capillary pressure. Such a trend can be explained by the non uniform initial saturation profile in the sample at the beginning of the experiment. The exact initial profile is difficult to obtain with the ultrasonic measurements because the sample is moved into a different core holder.

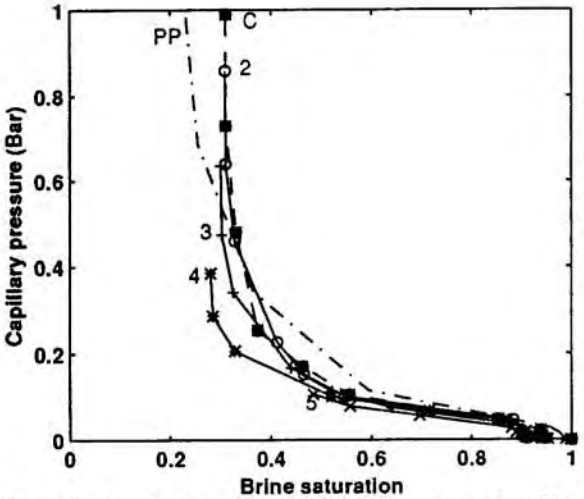

Fig. 5: Drainage Pc curves for sample S2. Direct determinations (2 to 5), computed curve (C) and air-water porous plate curve (PP).

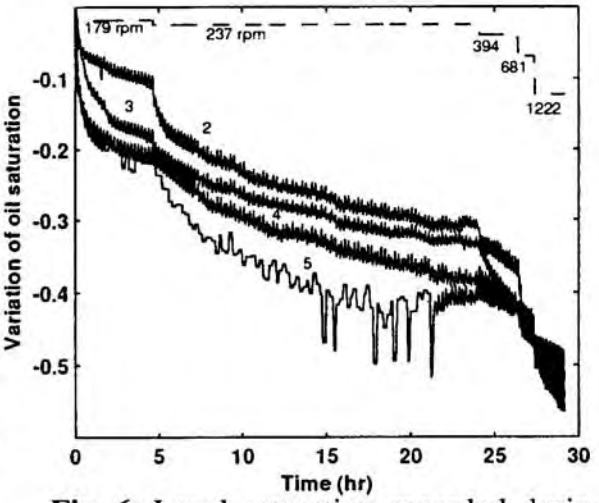

Fig. 6: Local saturation recorded during imbibition of sample S2. The fluctuations on channel 5 from 5 to 22 hr is due to noise.

Oil wet sample S3

This reservoir sample provided an example of a natural oil wet sample. During drainage, the water saturation decreased from 1 to 0.51 PV for a capillary pressure smaller than 3 mbar. The drainage Pc curve (not shown) has a L shape indicating a strongly oil wet system. For the forced imbibition experiment, fig. 8, the data indicate basically water entering the sample at the outer face (at R_{max}) and gradually displacing oil toward the inner face as the speed of rotation is increased. In this experiment, only three channels were available because of the small length of the sample. There is a threshold pressure (about 28 mbar or 419 rpm). The equilibrium times are quite large (about 5 hours), due to the low permeability of the sample (10 mD).The forced imbibition Pc curve (fig.9) is similar in shape to a drainage Pc curve of a water wet sample. For the range of pressure covered, the computed and direct determinations of the Pc curves agree (fig. 9). The residual oil saturation is low, as expected for an oil wet system.

Results: Relative Permeability Curves

The measurement of local saturation was expected reduce the uncertainties on the determination of relative permeability (Kr). Firoozabadi *et al.* (1986) showed that production data can be fitted with very different sets of relative permeability using Corey and Chierici power law descriptions. Nordtvedt *et al.* (1993) used spline functions to represent Kr curves, providing sufficient flexibility with a limited number of parameters. They showed that the

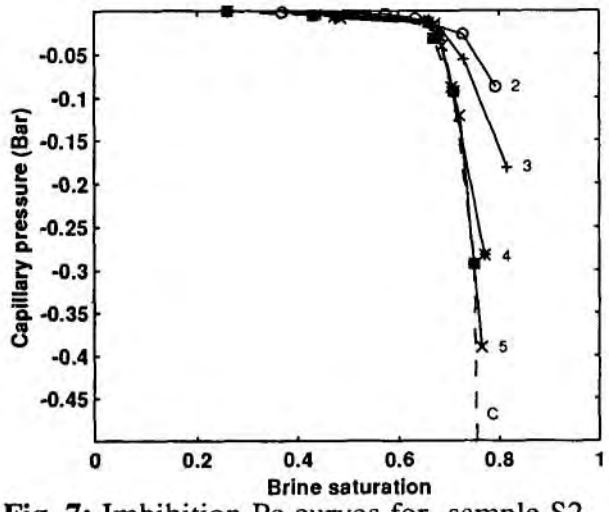

Fig. 7: Imbibition Pc curves for sample S2. Direct determinations (2 to 5) and computed curve (C).

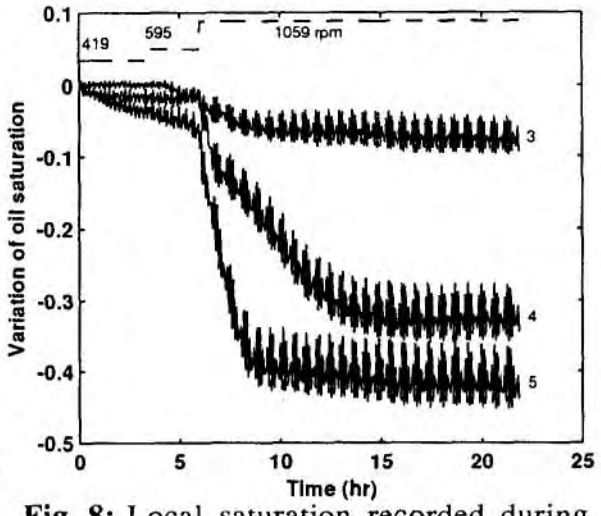

Fig. 8: Local saturation recorded during imbibition of sample S3. (oil wet reservoir sample).

confidence interval can be large when Kr curves are inferred from production data. Using for the first time local saturation measurements, Chardaire *et al.* (1992) found a good agreement between Kr curves obtained from unsteady state and centrifuge technique. However, the comparison between measured and simulated local saturation was not satisfactory. We focus here on the comparison between Kr curves obtained from local and average saturation measurements in order to highlight the specific problems arising when using local saturation. The average saturation was not measured continuously but was calculated from the integration of the instantaneous local saturation profiles (eq. 3).

The case considered is the drainage of the reservoir sample S2 of intermediate wettability described before. The data recorded during the quasi-spontaneous drainage (the nine first hours) were removed because the (negative) capillary pressure curve is not known in the saturation range covered ($0.9<Sw<1$). The problem is to identify the relative permeability curves in the saturation range [0.3 0.9] with an initial uniform saturation of 0.9. The numerical model used is a one dimensional two-phase incompressible model based on Darcy's law, as described in Chardaire *et al.* (1992). An error function, the sum of the squared difference between measured and simulated data, is minimised as described in Chardaire *et al.* (1992).

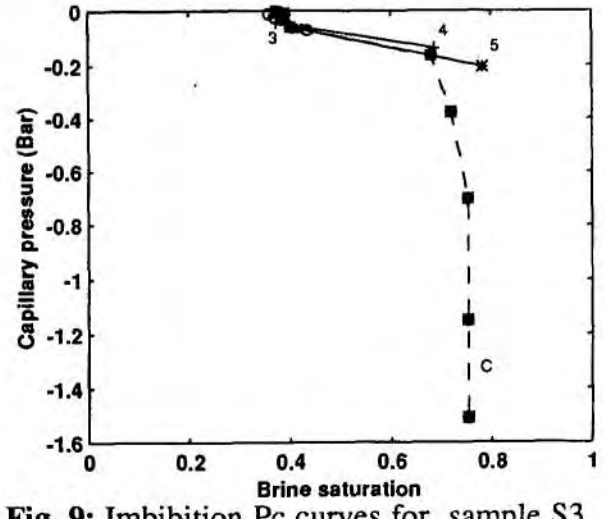

Fig. 9: Imbibition Pc curves for sample S3. Direct determinations (3 to 5) and computed curve (C).

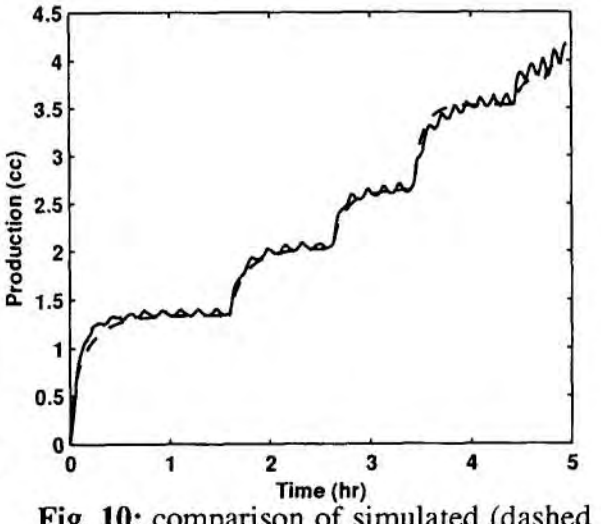

Fig. 10: comparison of simulated (dashed line) and measured production data using the production Kr curves from fig. 13.

The Kr curves were computed using

a) the cumulative production (fig. 10),
b) each local saturation separately (fig. 11). In this case, we obtain three sets of Kr curves from channel 2 to 4,
c) all local saturation measurements (fig. 12), as in Chardaire *et al.* (1992).

A good fit can be obtained from the computation a) and b) (fig. 10 and 11). In these computations, we used respectively the computed and local Pc curves slightly modified in order to reproduce the equilibrium saturation. The calculations are very sensitive to the capillary pressure curve due to the fact that the derivative dPc/dS actually used in the calculation may not be well estimated from the measured or computed curves. Especially where dPc/dS is small ("plateau"), a small increase of pressure generates a large variation of saturation. In computation c), we determined first the best Pc curve and then the Kr curves. However, the fit is poor (fig. 12) because the saturation at equilibrium at each location cannot be reproduced satisfactorily using a single Pc curve. This is due to errors of measurements and to weak heterogeneities of the sample. As a result, the error function is dominated by the saturation differences at equilibrium and the transient saturation values are not and cannot be properly exploited. Hence, even if the solution may be correct numerically, it is not convincing. In addition, such a situation may contain more local minima.

The five different Kr curves are compared in fig. 13. We used piece-wise linear segment to represent the curves with very large bounds for the first derivative (we identify the derivative of Kr in a range that can be chosen). No constraint on the second derivative is imposed contrarily to the spline representation. Such a representation is the most flexible one and certainly too flexible because fine details cannot be obtained from the data, even when local saturation are used. In fig. 13, we plotted the actual results (10 points per curve, values at Sw=1 are imposed) and a smooth average curve. The choice of the more appropriate curve is not obvious. When using local saturation measurements separately, there is a problem of averaging whereas, when all local measurements are used, the solution may be biased by the problem of unicity of the Pc curve. Thus, we conclude that local saturation measurements do not improve the determination of Kr curves. For "perfectly homogeneous sample", it can be demonstrated mathematically (Zhang, 1994) that the use of local saturation is better than production. Indeed, on synthetic data the error band around the identified Kr curves as well as the coupling between parameters is smaller. In practice, this is not confirmed by the above-described example and the advantages are not straightforward.

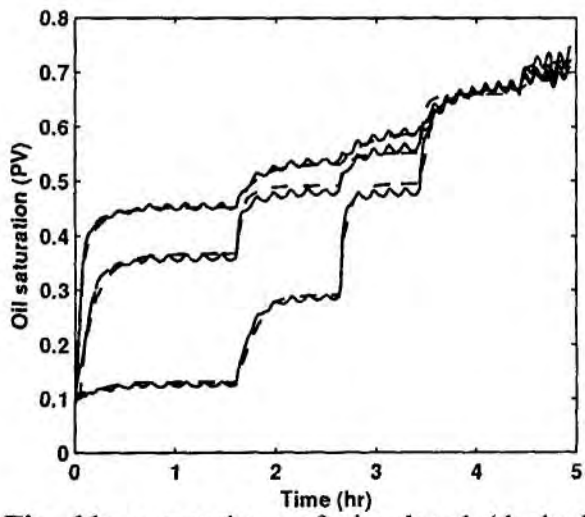

Fig. 11: comparison of simulated (dashed line) and measured saturation data at location 2 to 4 using the local Kr curves from fig. 13.

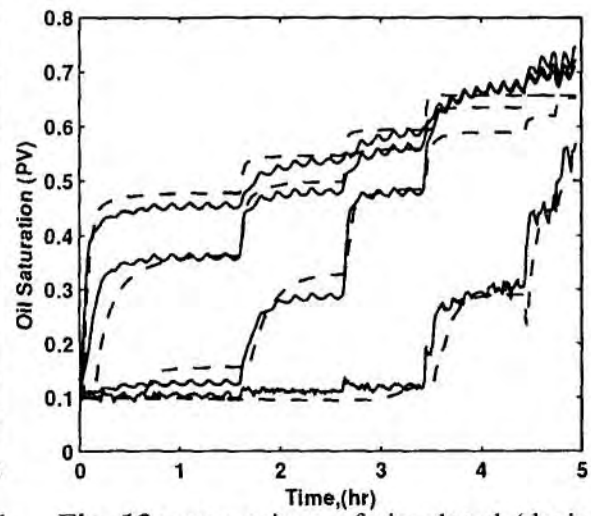

Fig. 12: comparison of simulated (dashed line) and measured saturation data at location 2 to 4 and using the all channels Kr curves from fig. 13.

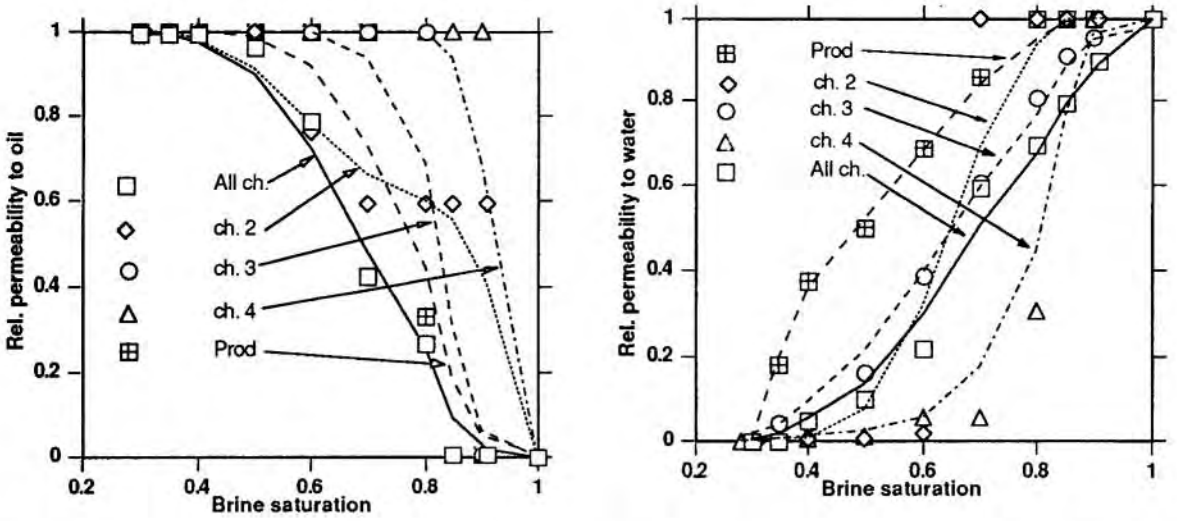

Fig. 10: drainage Kr curves computed using all the local measurements together (All ch.), each measurement separately (ch. 2 to ch. 4) and the production (Prod).

Conclusions

The measurement of saturation while centrifuging is very useful to study the kinetic of displacement processes. However, the method is difficult to calibrate because others parameters than saturation can influence the speed of sound in the porous medium. In particular, the effect of rotation is not well estimated and can be as large as the effect of saturation.

We did not observe any contradiction between the direct determination of the Pc curves and the computed ones, for any of the sample studied (from water wet to oil wet). Quasi-spontaneous processes that can take place at low speeds of rotation do not influence significantly the calculation. The measured saturation profiles are consistent with the assumptions of zero capillary pressure at the outflow face. The Pc curves obtained at the different locations were often different, although the samples used were not particularly heterogeneous. To avoid the problem of averaging, the computed Pc curve is more appropriate to characterise the sample, rather than a direct determination based on the measurement of the saturation in a thin slice of that sample.

Because the multi-speed centrifuge experiment is very sensitive to capillary pressure and weak heterogeneities, the local saturation measurements do not improve the determination of relative permeability curves. On one hand, very different sets of Kr curves are found locally using a simulator in which homogeneity is assumed and the choice of the more appropriate curves is difficult. On the other hand, characterising the heterogeneities of the sample for the simulator would probably be too complex. Thus, a precise recording of the average saturation (production), when properly analysed, should provide the information necessary to determine Kr curves with a reasonable confidence interval, as done for example by Nordtvedt *et al.* (1993).

Acknowledgements

This study is part of a project funded by AGIP, AMOCO, JNOC, MOBIL, NORSK HYDRO, SAGA, EAP, STATOIL and TOTAL. We thank these companies for their support.

Nomenclature

a,b	calibration coefficient
Kr	relative permeability (fraction)
K	absolute permeability
L	sample length
Pc	capillary pressure (oil/brine pressure difference)
R	radius of rotation
R_{min}, R_{max}	radii of rotation of the faces of the sample
S_w	brine saturation
S_o	oil saturation
S_i	oil saturation at location x_i
t	transit time
t_o	transit time taken as reference at Sw=1
t_c	correction of transit time for the rotation effect
t_i	characteristic time for an imbibition process
x_i	distance from R_{min}
μ_o	oil viscosity
α	correction coefficient for the rotation effect
σ	oil/brine interfacial tension
ω	speed of rotation

References

Bacri J.C. and Salin D., "Sound velocity of a sandstone saturated with oil and brine at different concentrations", Geophys. Res. Let., 1986, vol. 13, pp 326-328.

Baardsen H., V. Nilsen, J. Leknes and A. Hove, "Quantifying saturation distribution and capillary pressures using centrifuge and computer tomography", NIPER/DOE , 1989.

Chardaire-Riviere C., P. Forbes, J F Zhang, G Chavent and R. Lenormand, "Improving the centrifuge technique by measuring local saturation", SPE 24882, 1992.

Cuiec L.E., B. Bourbiaux and F. Kalaydjan, "Imbibition in low-permeability porous media: understanding and improvement of oil recovery", SPE/DOE 20259, 1990.

Cuiec L.E, "Evaluation of reservoir wettability and its effect on oil recovery, in Interfacial phenomena in petroleum recovery", ed. N.R. Morrow, Marcel Dekker INC., 1991.

Deflandre F. and R. Lenormand, "Laboratory measurement of oil/water saturations by an ultrasonic technique", Proceedings of Third European Core Analysis Symposium, Paris, 14-16 Sept. 1992.

Firoozabadi A. and K. Aziz, "Relative permeability from centrifuge data", SPE 15059, 56th SPE meeting, April 2-4 1986.

Forbes P.L., "Simple and accurate methods for converting centrifuge data into drainage and imbibition capillary pressure curves", SCA 9107 presented at the SCA conference, San Antonio, August 20-22, 1991.

Forbes P., C. Chardaire-Rivière, F. Deflandre, M. Fleury, "Local saturation measurement while centrifuging (MWC) for improving centrifuge capillary-pressure curve determination", SCA 6th meeting, 1992, Oklahoma-City.

Forbes P., Z.A. Chen and D. Ruth, "Quantitative analysis of radial effects on centrifuge capillary pressure curves", SPE 28182, 1994.

Nortvedt J.E., G. Mejia, Pin-Huel Yang and A.T. Watson, "Estimation of capillary pressure and relative permeability functions from centrifuge experiments", SPE Reservoir Engineering, November 1993.

O'Meara D.J., G.J. Hirasaki and J.A. Rohan "Centrifuge measurements of capillary pressure; Part 1-Outflow boundary condition", SPE 18296, 1988.

Radke C.J., A.R. Kovscek and H. Wong, "A pore level scenario for the development of mixed wettability in oil reservoirs", SPE 24880, 1992.

Zhang J., "Sensibilité et stabilité dans l'estimation des permeabilités relatives et de la pression capillaire à partir de mesures de laboratoires", Ph. D. dissertation, Université Paris IX Dauphine, , 1994, in french.