COMPARATIVE STUDY OF DRAINAGE CAPILLARY PRESSURE MEASUREMENTS USING DIFFERENT TECHNIQUES AND FOR DIFFERENT FLUID SYSTEMS

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Abstract

The determination of representative capillary pressures (Pc) is needed for the forecast of the fluids distribution in the reservoir. The initial water saturation and the accumulation depend directly on this parameter. However variations between measurements obtained by various standard techniques (mercury injection, porous plate, centrifugation) or for different fluid systems have been often observed and reported in the literature.

This study tries to establish relationships between drainage Pc curves obtained from various techniques. With this goal, a series of drainage experiments was systematically achieved on samples from various lithological facies and with different core properties, with the samples having been made as water-wet as possible.

The comparison of these measurements leads to the following observations:
- for the air-brine system, both of the techniques (porous plate, centrifugation) fit accurately on the majority of the samples in spite of different cleaning procedures and sample sizes, with moreover a good agreement of the mercury injection Pc curve using a suitable scaling factor,
- the Pc/σ curves for the three pairs of fluids have the same relative position for each sample (where σ is the interfacial tension of the fluid system),
- the maximum gas saturation for an air-oil drainage is close, although always superior, to the one for the air-brine system. On the contrary, a systematic 5 to 10 saturation unit difference is observed between the asymptotic limit of gas-liquid and oil-brine Pc curves.

With regard to a gas-liquid system and for fairly clay free samples, the three techniques appear to be valuable to describe the capillary balance. Oil reservoirs must be subject to particular measurements in order to estimate the oil-brine system behaviour. Drainage centrifuge experiments using pseudo reservoir fluids are then qualified to provide reliable data.

Introduction

The three main techniques of Pc measurements in the Petroleum industry are centrifugation, porous plate and mercury injection. The two first methods can be used in various conditions of temperature, stresses or with different fluid systems. Using these capillary pressures in reservoir engineering often requires to adapt these curves to reservoir conditions. The degree of validity of this transformation is not always known. The laboratory measurement representativity will depend on its application and will change from one technique to another. Our knowledge of these techniques, their range of validity and their field of representativity needs to be improved for a better use of measurements.

The aim of this study is to clarify these points, by comparing a large number of drainage capillary pressure measurements using different techniques and for different fluid systems.

Experimental program

The experimental program is summarized in Table 1. Firstly, a set of six "big plugs" (40 mm in diameter, 40 to 50 mm in length) with another set of six companion "small plugs" (23 mm in diameter, 23 mm in length) from various lithological facies and with different core properties were selected. These samples are described in Table 2 and their mineralogical composition is given in Table 3.

cleaning procedures

The "small plugs" were cleaned using soxhlet technique with chloroform at 80°C, then dried in an oven. The "big plugs" were mounted in individual cells and cleaned by injection of miscible solvents (toluene, toluene-isopropanol, isopropanol), then dried in an oven. This procedure aimed at making the samples as water-wet as possible and was identically repeated before each centrifugation experiment. All experiments were carried out at ambient conditions (21°C, atmospheric pressure) using nitrogen, laboratory brine and refined oil so that wettability could remain constant. After cleaning, porosity and density were accurately measured before each experiment by immersion in mercury (total volume) and by helium injection (matrix volume).

porous plate and mercury injection

The "small plugs" were placed in a capillary pressure cell, where they were fully saturated with brine after imposing a vacuum, and they were weighed individually. The pressure in the air was increased by successive stages, the pressure in the water was kept constant thanks to a semi-permeable porous plate on which the sample rested. At each step the air expelled the water out of the samples until stabilisation of the total weight. Samples were then removed from the cell and weighed individually in order to determine saturation. Drainage was conducted at intermediate stages of 0.250, 0.500, 1, 2, 3 bar up to 4 bar of capillary pressure.

Mercury injection was then conducted on these samples at incremental pressures until 4000 bar when the pore network was completely flooded. The wetting fluid was represented by vacuum. This technique is destructive for the samples.

centrifugation

The "big plugs" were placed in a capillary pressure cell and fully saturated with wetting fluid (brine or oil) after imposing a vacuum. The samples after being weighed were loaded into a sample holder and centrifuged at increasing speeds. Expelled brine was collected in a tube and the volume was determined automatically by a specific program using a stroboscope adjusted to the centrifuge speed and a camera. Rotation speeds and running times were computed and the centrifuge run was automatically monitored.

Drainage centrifuge experiments were carried out on each plug for three pairs of fluids (air-brine, air-oil, oil-brine). Maximum duration times at each step were 6 hours for the air-brine run and 8 hours for the air-oil and oil-brine runs.

The pressure difference between the two fluids is a function of the density difference. A saturation profile is developpped along the sample because of the variation in acceleration. The average saturation is then corrected to the true saturation with the help of the Forbes program.

Results and discussions

Comparison of techniques

Pc curves for the air-brine system are shown on Figures 1 through 6 obtained by porous plate and by centrifugation. Capillary pressure obtained by the mercury injection has been added using a suitable scaling factor :

$$\text{Pc air-brine} = \frac{\text{Pc vacuum-mercury}}{6.85} \qquad \text{with} \qquad 6.85 = \frac{\sigma(\text{vacuum-mercury})}{\sigma(\text{air-brine})}$$

A good agreement between the capillary pressures from the three methods is obtained The curves coming from the porous plate and mercury injection techniques applied on the same plugs fit accuratly for 5 samples. Only a 7 points deviation can be noticed between the two asymptotic branches of the first sample. Air-brine centrifugation curves are situated above the porous plate curves at high saturations for three samples (1, 4, 5) and at the same level for samples 2, 3 and 6. These differences are due to kinetic reasons : waiting time at each centrifugation step (6 hours) was too short for the less permeable samples. But the residual saturation values are the same for both techniques on all samples. From the observations we can deduce that :

the porous plate technique is reliable enough to be used in spite of long experimental duration times and difficulties of measuring, and this method is the most representative of the drainage physical process into the reservoir,

- the mercury injection technique is repetitive and reliable, and give representative air-brine capillary pressures in the range 0-5 bar in case of clay free and initially water wettable samples,
- the reconciliation of measurements justifies the use of a scaling factor (6.85) equal to the ratio of the involved fluid system interfacial tensions, which means to neglect the contact angle,
- the centrifugation technique enables to obtain valid capillary pressure curves by achieving simple and short experiments with appropriate duration time and with necessary weight controls at the beginning and at the end of the drainage. This method is particularly advantageous to determine the residual saturations,
- the cleaning procedure used on "big plugs" before centrifugation tests gives a water wettability, equivalent to the one obtained after cleaning "small plugs" with chloroform. Using refined oil enables us to keep constant the state of wettability during experiments,
- no size effect is observed. The size of sample used for each technique appears, therefore, to be correctly adapted.

Comparison of fluid systems

The centrifuge drainage measurements achieved with the air-brine, air-oil and oil-brine systems and the mercury injection measurement for the mercury-vacuum system are shown in $Pc/\sigma = f$ (S wettable fluid) on Figures 7 to 12, σ being the interfacial tension of the fluid system. The air-oil Pc curves are situated above the air-brine curves and a 3 to 8 points difference is observed on final saturations. The agreement is correct for permeable sandstones ($k > 100$ md) 1, 3 and 6, and for the first porosity of the oolitic limestone (sample 5). For samples 2 and 4, the deviation can not be explained by the clay content or water wettability, which would favour water retention, but more by kinetics. Because of the viscosity difference (2 cp for oil, 1 and 1.2 cp for brine) and low duration time (6 hours for air-brine, 8 hours for air-oil) at each centrifugation step, the level of stabilization at the end of each rotation speed is not the same for both fluid systems, especially in case of low permeability samples. Duration times of 10 hours for air-brine and about 20 hours for air-oil would have probably been more adapted.

Oil-brine capillary pressures for high saturations are 1 to 2 times lower than air-brine Pc, as the oil-brine asymptotic part is in all cases at a clearly higher saturation than for air-brine (about 10 saturation points). This strengthens the 7 points deviation observed in 1991 by Longeron (ref. 4) and the idea that capillary pressures measured for a gas-liquid system are not adaptable to a liquid-liquid system. This is probably due to different drainage processes but only a microscopic observation of the porous media could inform us more precisely.

Influence of wettability and clay content

The contact angle enables to take into account the affinity of the involved fluids for the rock. The complexity of porous media, the heterogeneity and rugosity at the pores surface imply that the contact angle has less influence on Pc than the one described by theory and that we could expect. Morrow (ref. 5), after numerous tests, concluded that contact angles could be neglected for theoretical values less than 50°. Purcell (ref. 9) observed a better reconciliation between porous plate and mercury injection Pc curves, using a contact angle value θ=0°, although he measured a value equal to 140° for the mercury-vacuum system.

In our study the most accurately reconciliation between air-brine and mercury-vacuum capillary pressures is achieved when we neglect the wetting angle for both fluid couples. It is then reasonable to assume that the air-oil contact angle is also equal to zero.

The clay content influence on Pc was not observed on the six selected samples. Indeed the clay proportion is too low (7 % maximum) and comparison is done on a 0-5 bar scale only. Fig. 16 plots the saturation difference at 80 bars between mercury injection and air-brine centrifugation versus clay percentage for 12 sandstone plugs coming from a North Sea gas reservoir. A trend is obvious. A saturation divergence appears when clay content represents more than 7 % of the mass and increases with clay percentage. It can be over 20 saturation points (Figure 15) for a sample which contains 20 % of kaolinite with a "pore-bridging" disposition (dickite). Mercury injection does not take into account the presence and the role of clays in air-brine capillary balances. Mercury-vacuum capillary pressures are in that cases not suitable to describe an air-brine system.

Conclusions

From all these tests carried out on six cleaned and water wettable samples, the following conclusions can be made :

- For the air-brine system, the porous plate and centrifugation techniques give close results. Both cleaning procedures give equivalent water wettability and the size effect seems negligible. Mercury injection leads to the same results as well, when we consider a scaling factor equal to the interfacial tensions ratio and a contact angle equal to zero.

- Mercury injection is a repetitive and short time method but representativity of the capillary pressures is doubtful fo high clay content porous media.

- Centrifugation is a reliable technique to obtain easily and quickly representative capillary pressures and saturation limits. It is nevertheless necessary to determine carefully duration times at each rotation speed according to the permeability of the sample and the viscosity of the fluids.

- For highly permeable sandstones (k>100 md) the drainage air-brine capillary pressure curves are usable for air-oil systems. For carbonates and low permeability samples air-oil tests are preferable to describe air-oil capillary balances.

- Capillary pressures for a gas-liquid system are not transposable to a liquid-liquid system. Oil-brine capillary pressure measurements are then necessary to study oil-brine interactions.

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Nomenclature

Pc	:	capillary pressure
S	:	saturation
σ	:	interfacial tension
θ	:	contact angle
ϕ	:	porosity
k	:	monophasic permeability
Swi	:	initial water saturation
Sor	:	residual oil saturation
ρ	:	density

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Table 1 : Experimental program

measurement technique	centrifugation			porous plate	mercury injection
Fluids system	air-brine	air-oil	oil-brine	air-brine	mercury-vacuum
6 small plugs				X	X
6 big plugs	X	X	X		

Table 2 : Sample characteristics

N°	Facies	ϕ (%)	k (mD)	ρ (g/cm3)
1	sandstone	22.8	112	2.69
2	dolomite	28.7	23	2.85
3	Vosges sandstone	23.7	109	2.66
4	clay sandstone	22.7	7	2.66
5	oolitic limestone	19.0	27	2.71
6	sandstone	22.2	612	2.66

Table 3 : Mineralogical composition (%)

N°	feldspaths	quartz	anhydrite	calcite	dolomite	clays	others
1	10	83	traces	3	0	4	traces
2	traces	1	4	2	88	2	3
3	22	73	0	0	1	3	1
4	2	87	0	4	0	7	traces
5	traces	2	0	98	0	traces	traces
6	5	89	0	2	0	4	traces

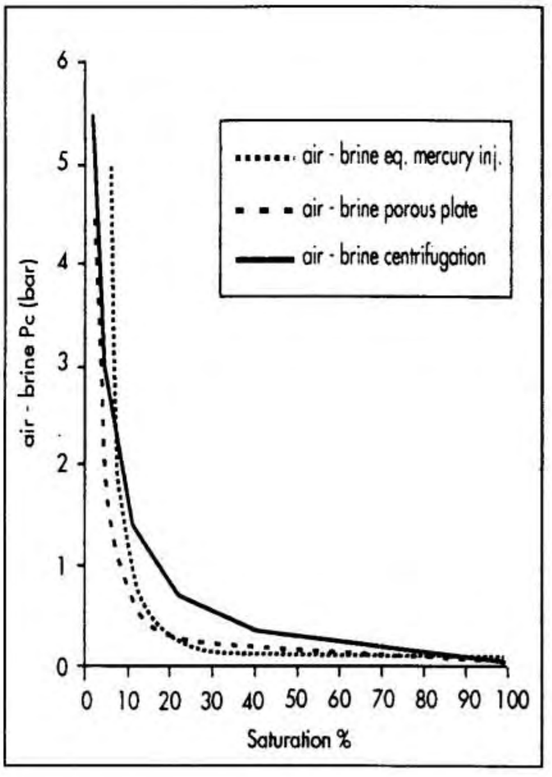

Fig1 : Comparison of techniques on sample 1

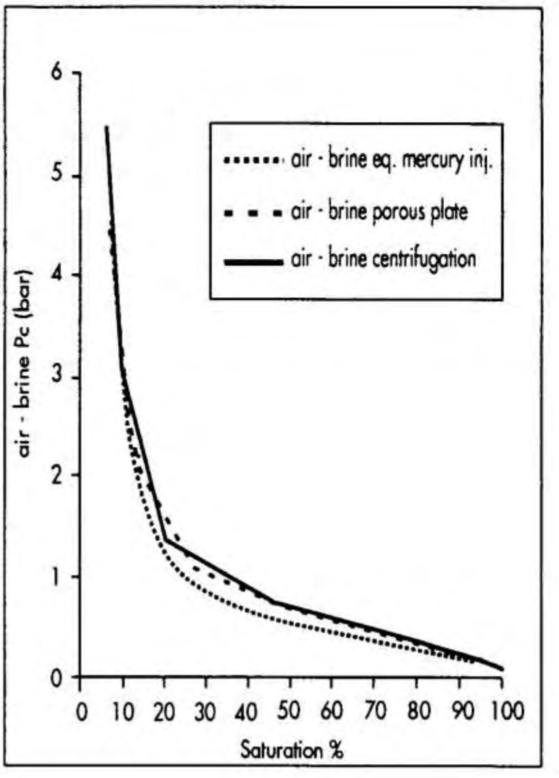

Fig2 : Comparison of techniques on sample 2

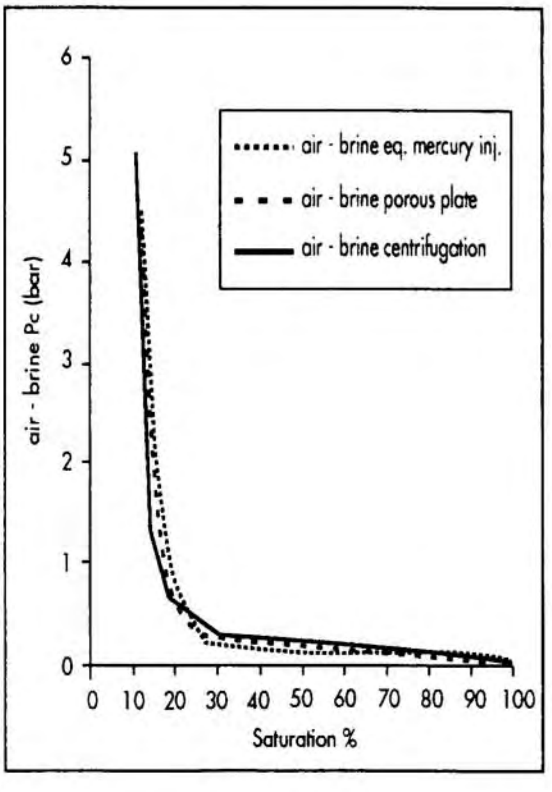

Fig3 : Comparison of techniques on sample 3

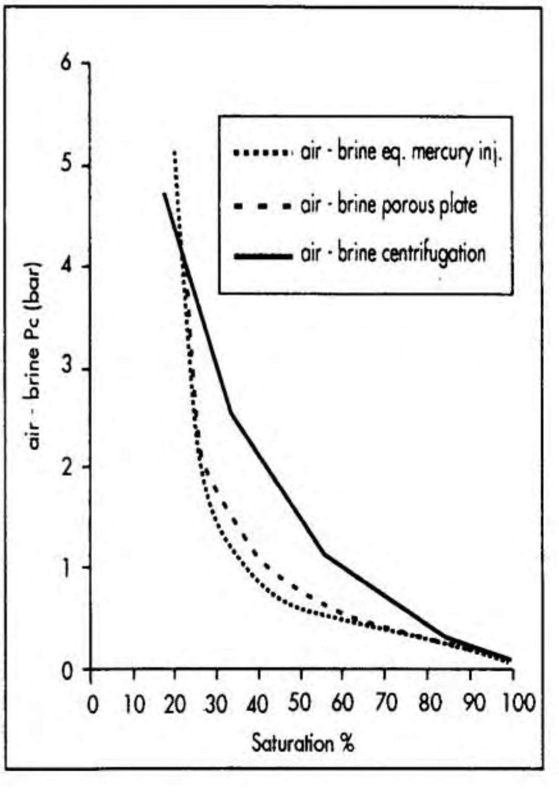

Fig4 : Comparison of techniques on sample 4

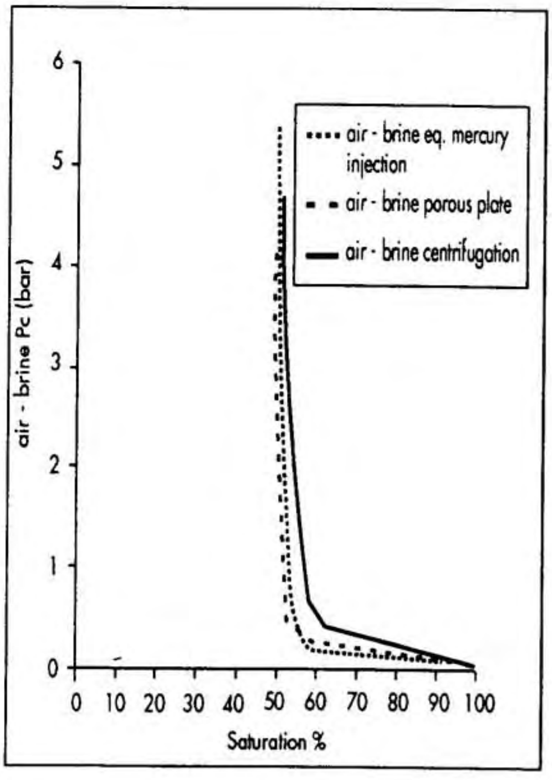

Fig5 : Comparison of techniques on sample 5

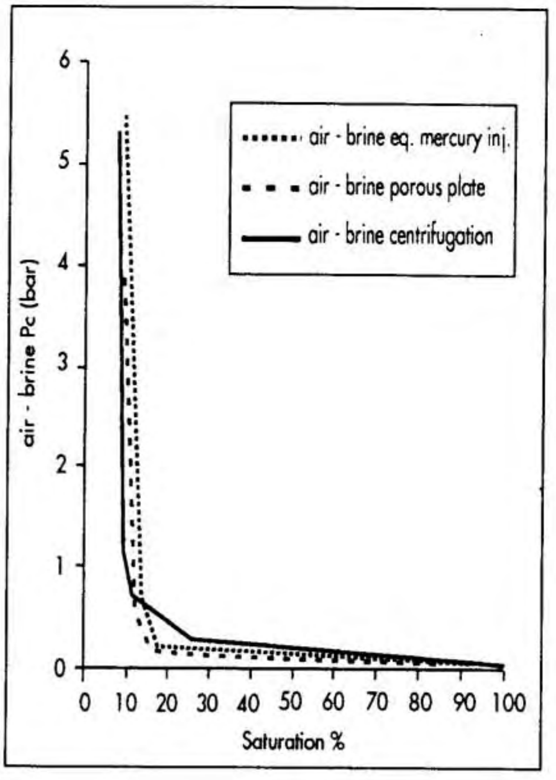

Fig6 : Comparison of techniques on sample 6

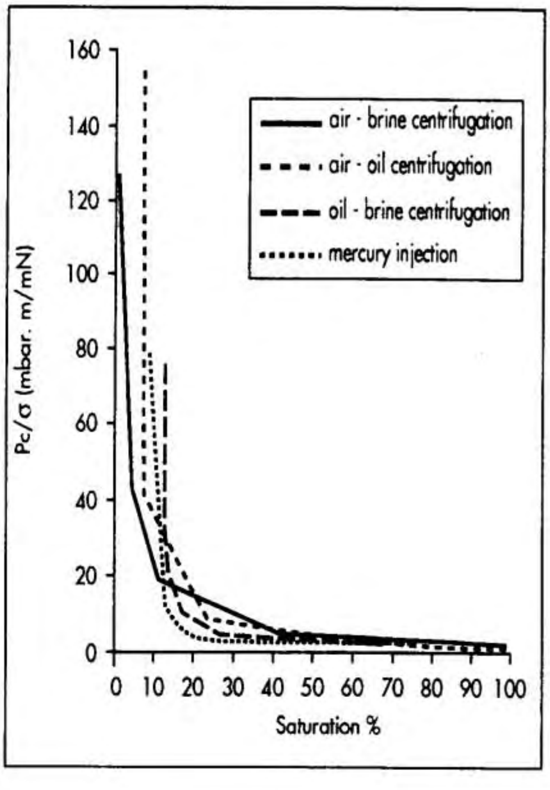

Fig7 : Pc/σ comparison on sample 1

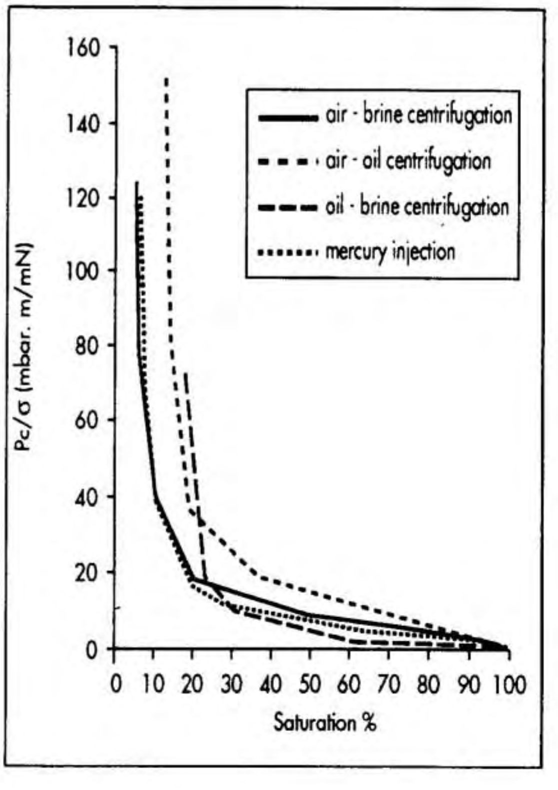

Fig8 : Pc/σ comparison on sample 2

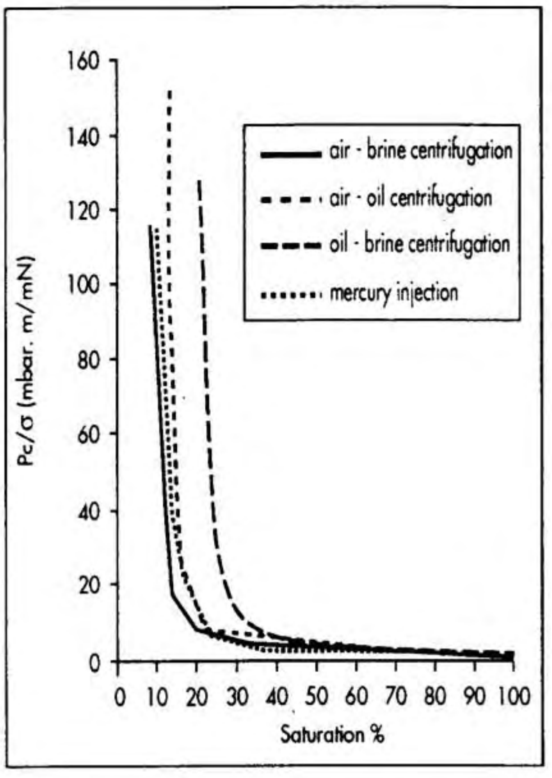

Fig9 : Pc/σ comparison on sample 3

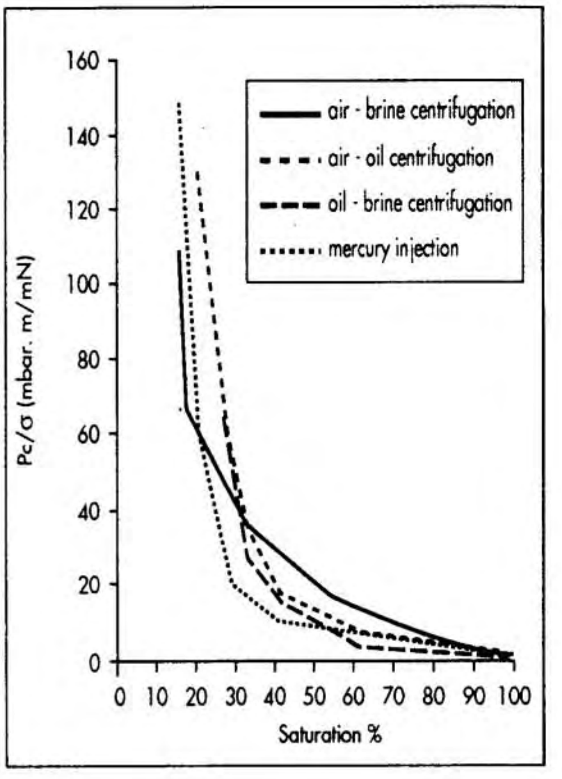

Fig10 : Pc/σ comparison on sample 4

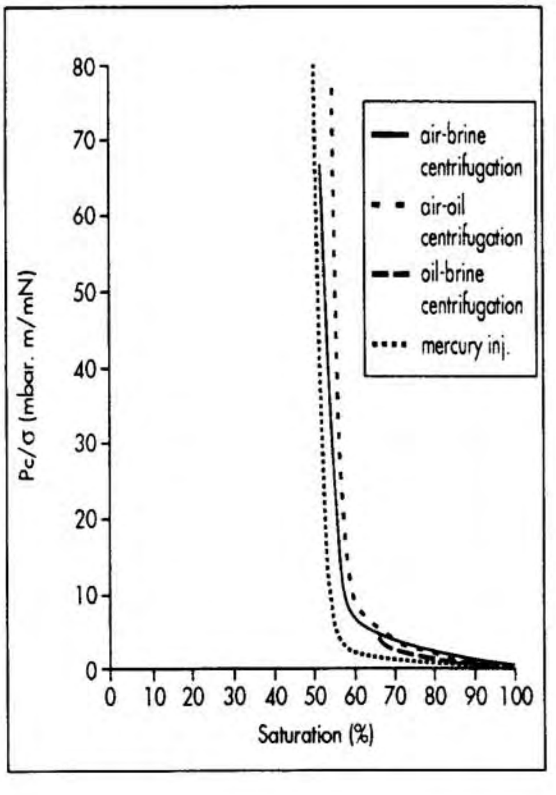

Fig11 : Pc/σ comparison on sample 5

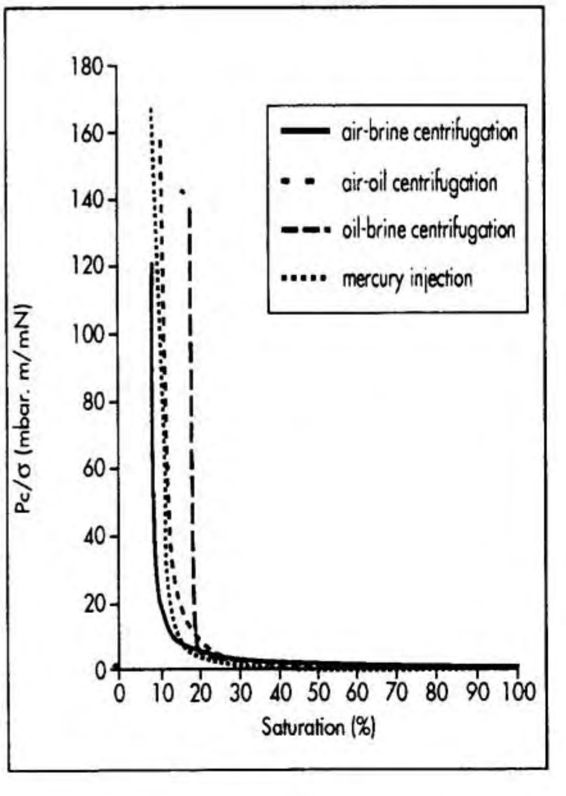

Fig12 : Pc/σ comparison on sample 6

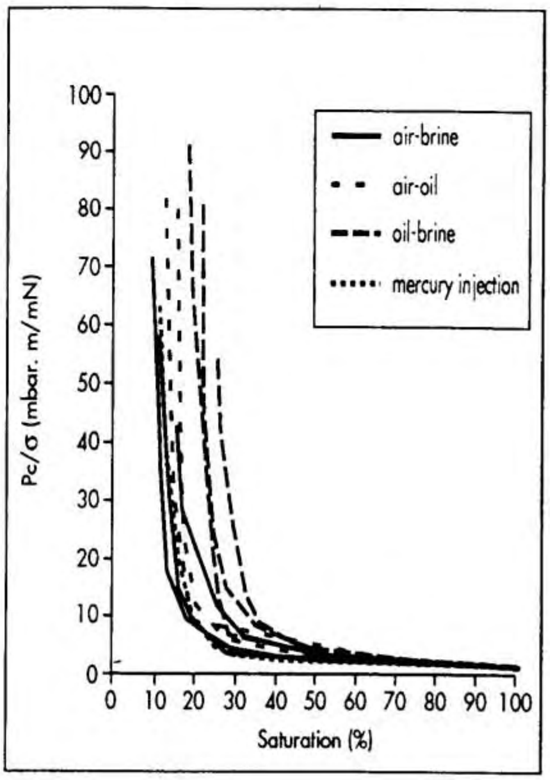

Fig13 : Fluid system comparison on sample3

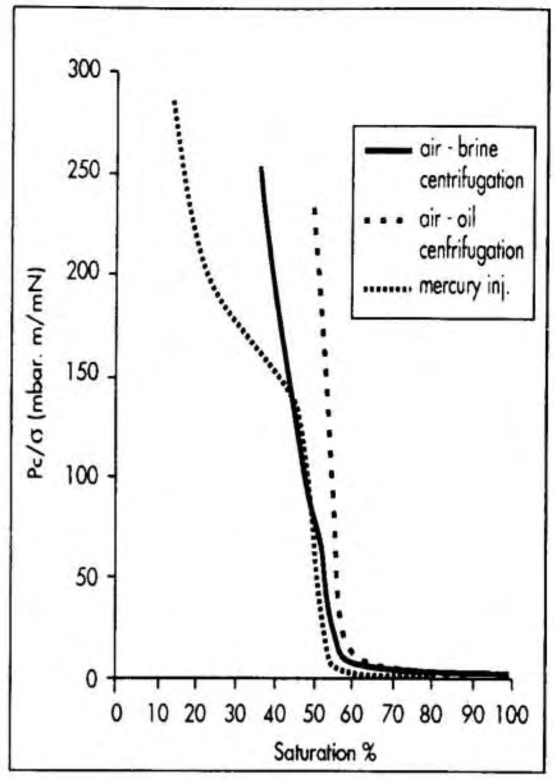

Fig14 : Comparison on double porosity sample 5

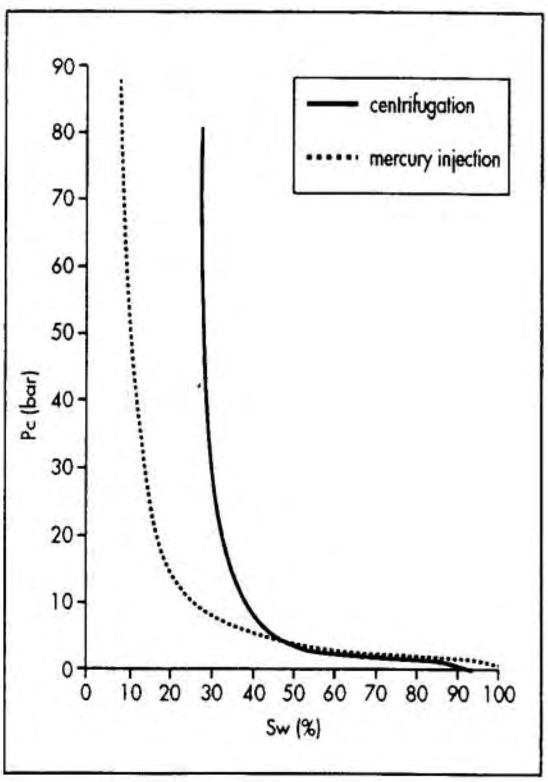

Fig15 : Pc comparison on a sample with 20 % of clay

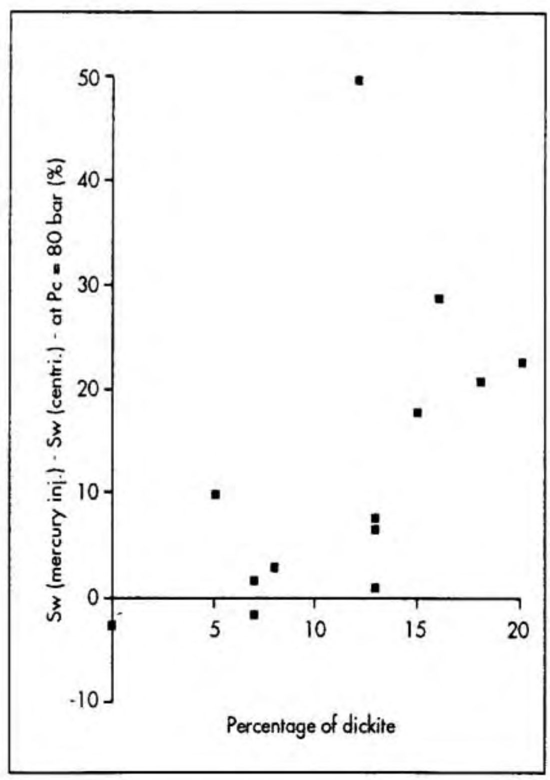

Fig16 : Δ Sw at Pc = 80 bar versus clay content