Resistivity measurements while centrifuging

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Abstract

Resistivity indices can be obtained during capillary pressure measurements using the porous plate or the membrane method. This paper describes an alternative method based on the centrifuge technique. The main idea is to use "rotary contacts" in order to record intensity and potential while centrifuging. In addition, a radial "four electrodes" setting is used. In such a way, resistivity is measured through a thick rock slice at the middle of the sample. Both techniques, rotary contact and radial electrode geometry, have already been used and tested for other purposes. Nevertheless, specific problems remained. Some were experimental: how to keep a good contact between the electrodes and the sample while minimizing the weight and volume of the device. This has been solved by an original (and patented) method that ensures both electrode pressure and sealing of the lateral face of the sample. The second kind of problem met was the non-uniformity of the saturation due to the centrifugation process. A simulation of the resistivity index values depending on local or mean saturations is proposed. In the calculation, the local saturation is derived from the local capillary pressure curve (Forbes'method). The conclusion of this study is that reliable resistivity indices and Pc curves can be simultaneously obtained by centrifuge measurements. Application to reservoir rocks is begun.

Introduction

Capillary pressures and resistivity indices are parameters which constrain the reserve evaluation and the results of reservoir modeling. The quality of these results depends on the quality of the input data, themselves depending on experimental procedures. It is thus of importance to get consistent sets of values on well characterized cores. That is why simultaneous measurements of these parameters are likely to provide a consistent set of input parameters. They allow time saving while measuring, which is quite important with respect to the duration of physical phenomena. In addition, they favor a better understanding of the production phenomena, and allow correlation with other characteristics of the cores, like the mineralogy and the distribution of clays within the porous space. Simultaneous measurements of capillary pressure and resistivity indices have already been achieved by Fleury and Longeron (1996). They used a special shape for samples, and a specific setting for the electric measurement. This setting allows a ‘‘four electrodes” measurement which prevents problems arising from contact resistances.

As centrifugation is an alternate method for capillary pressure measurements, we attempted also to simultaneously measure the resistivity indices. The specific problems set by the use of centrifuge are the weight of the rotating device, the transmission of current, the way of applying the electrodes against the rock samples, the non-homogeneity of the saturation in the sample.We will show the solutions that have been found to these problems.

Experimental

- **Device design**

The aim of the experiment is to measure continuously the resistance of the porous medium during the drainage/imbibition procedure. Several papers (Baldwin et al. 1989, 1991, Baardsen et al.,1989) have already addressed the problem of fluid redistribution after centrifugation. The possibility to measure continuously any property (e.g., resistivity index), is likely to allow discarding of spurious data due to this redistribution. In addition, the array of electrodes in a radial geometry, as formerly used in CAPRIWET (Fleury and Longeron, 1996) prevents problems arising from a longitudinal measurement when the samples are centrifuged (Sprunt et al, 1988, 1990). Furthermore, the definition of the « plateau », (i.e. the state of equilibrium), or at least of a meta-stable state, corresponding to a specific rotation speed (i. e. a capillary pressure), can be done with a better confidence when the evolution of the resistance is checked in addition to that of the fluid production.

A necessity for centrifugation is a light weight of the rotating assembly, samples and accessories, and this is fulfilled by using small samples and minimizing the weight of the accessories. The sample is a cylinder, of defined diameter and length, coated in a insulating polymer casing. In the middle of the casing, six electrodes are set radially, three by three. The electric wires are related to the current generator and voltmeter, or impedancemeter, through rotating contacts. These contactors were already tested in a ultra-sound application (Forbes et al, 1992, Fleury et al, 1994). Another solution would have been the use of an optical transmission as in Ruth et al. (1996).

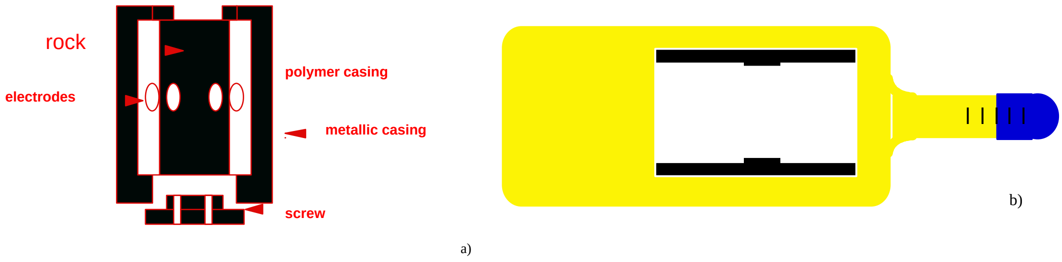

Figure 1: Scheme of the electrodes array along the core sample(a). The screw compresses the polymer casing between the metallic casing and the core in order to apply the electrodes against the core. The core is then put in the centrifuge coreholder (b).

The pressure to apply the electrodes on the core is not applied by a gas, like in a Hassler cell, which would be too heavy. An original solution is found (patent pending). The pressure is applied either by a compression kit shown on figure 1, or by a thermoretractable casing. The latter apparatus is lighter, and is preferred when linking the drainage and imbibition steps. The casing ensures a good contact between the electrodes and the rock, preventing oil drops from getting trapped at the interface. In addition, it prevents the exchange between the core and the surrounding fluid from taking place by the cylindrical face. The electric circuit is shown on figure 2.

The sample is put in the centrifuge coreholder, at the bottom (drainage)/ top (imbibition) of which a transparent tube allows reading of the produced fluid during drainage/imbibition. Preventing the entry of oil or brine on the electric contact is a difficult problem, which is solved satisfactorily in drainage, but is still being improved in imbibition.

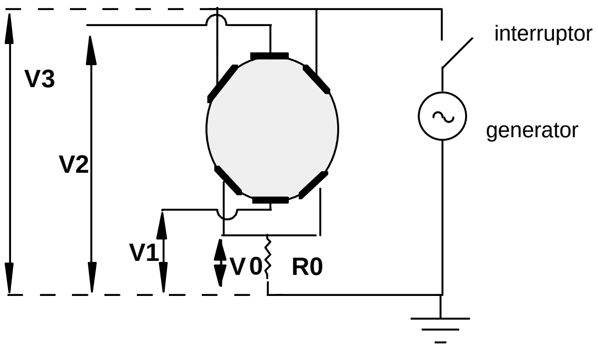

Figure 2: Electric circuit

Strapping the electrodes allows us to calculate the resistance of the porous medium either with a “two electrodes” setting, or with a “four electrodes” setting, which is recommended to prevent the contact resistances from disturbing the measurement. Having these two values proved useful when preliminary experiments failed: the diagnosis of oil drops trapping at the surface of the electrodes is made easier when looking at the values reached by the « two electrodes » resistance value.

The centrifuge is a Jouan KR4.22, with a maximum radius at the bottom of the sample about 20 cm, and the maximum speed used is 3000 ± 10 rpm, but the speed changes may reach an overvalue about 10 %. The temperature regulation is ± 2 °C, the usual temperature is 20°C. The samples can be 2 or 4, up to 40 mm diameter and 80 cm long. In the present study, the samples were all 23 mm diameter, 4 to - cm long, and only two samples were ran at the same time.

- **Choice of samples**

To check the apparatus, the first experiments are made with Fontainebleau sandstones, which are pure quartz, with various porosities and permeabilities, then with a Vosges sandstone, already used in previous studies (Durand et al., 1991, Souto, 1994). We characterized the Vosges sandstone once more, in order to check the reproducibility of the sampling, which is fairly good. The porosity is 22 ± 1vol- %, the permeability 100 ± 25 mD. Mineral composition is given in Table I.

Further experiments are made on reservoir samples, already characterized in previous studies. These samples, coming from oil zones of the North Sea, are cleaned with solvent in order to be as water wet as possible. The brine is reconstituted from the analysis of the formation brine. Its conductivity is measured at given temperatures. The oil is Soltrol 130, which is mainly a C12 cut.

Table I. Mineral composition of the Vosges sandstone and reservoir rocks (wt-%),

	GV	**3445**	**CAR1**
Quartz	61.87	70.8	83.7
K-Feldspar	20.18	11.2	0
Illite	15.33	3.3	13.8
Kaolinite	0.81	6.7	0
Albite	0.55	6.8	0
Rutile	0.43		
Hematite	0.84		

• Geometrical factor and formation factor measurements

Due to the shape and arrangement of electrodes and to that of the sample, the volume in which the current passes is not a simple geometric shape. Thus the radial setting is difficult to calibrate. So we measure the resistance of a plug of the defined geometry (a cylinder, 23 mm diameter, 40 mm long) both longitudinally and radially, in order to get a « geometrical factor » corresponding to the setting. This is done on two Fontainebleau samples, with different salinity brines, and on three companion samples of Vosges sandstones, with the reconstituted brine. For both sets of samples the ratio of resistance is radial/longitudinal = 0.5 as shown on figure 3. This shows that the electric measurement involves a volume equivalent to half of the one measred in the longitudinal setting, and is thus not as local as expected. The formation factors are 12.5 and 11 for Fontainebleau, and 11 for the Vosges sandstone.

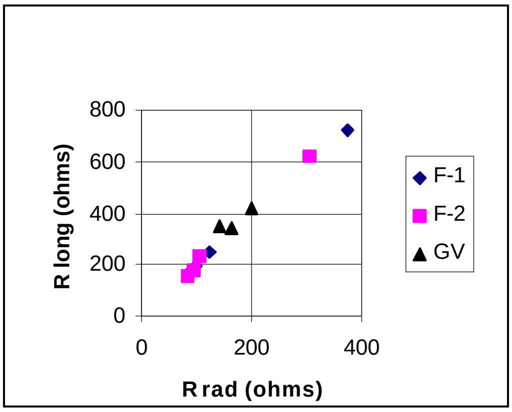

Figure 3 : Determination of the geometrical factor radial vs. longitudinal

• Drainage experiments

The run of drainage experiment of Vosges sandstone (gresII, gresVII) is made with the setting shown on figure 1, on samples 23 mm diameter, 40 mm length. The results of resistance measurements and capillary pressure are given as a function of the mean brine saturation calculated from the produced brine (figure 4).

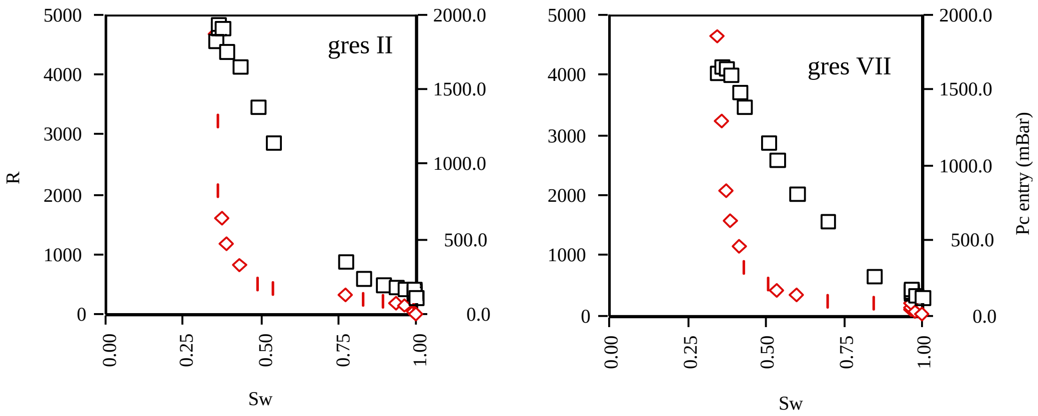

Figure 4: Capillary pressure at entry calculated from rotation speed, in mBar, (diamonds) and resistance measurements in ohms(squares) as a function of mean saturation calculated from production

As the samples used are small, the volume of the produced fluids are small, and the uncertainty on the saturation may be relatively high. The value of the mean saturation is checked by extracting the residual fluids in the plug by a miscible solvent (isopropanol), and analyzing the water by the Karl Fischer method, and the hydrocarbons by gas chromatography. For water the results are within 0.1 ml, which is fairly good, and fits with the experimental precision of the reading. This gives a precision in the saturation of about ±3 vol%. For hydrocarbons, the results are somewhat higher than calculated by difference: this can be explained by a residual film at the surface of the core : 0.3 ml corresponds to a film at the external surface of the core about 0.1 mm.

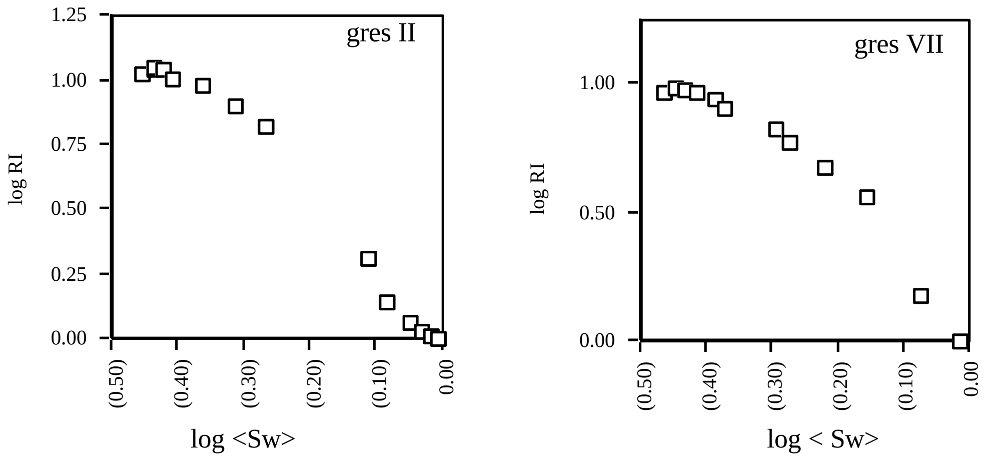

Figure 5: Resistivity indices as a function of mean saturatio).

The resistivity indices are shown as a function of the mean saturation in figure 5. The curves are not straight lines, and this can be qualitatively explained by the fluid distribution as follows : at low rotation speeds, the oil flow is not yet « seen » by the electrodes, which are located at the middle of the sample length and the resistivity index is low. At high rotation speeds, the oil front is already passed, and the electrodes « see » mostly a zone where the oil saturation thus the resistivity index, is high. A similar behavior has been found by Sprunt et al (1991) using another pressure variation device.

The local saturations induced by centrifugation within the sample can be calculated starting from the mean saturations as a function of the capillary pressure by using Forbes'algorithm (1991). The result of this adjustment is shown on figure 6.

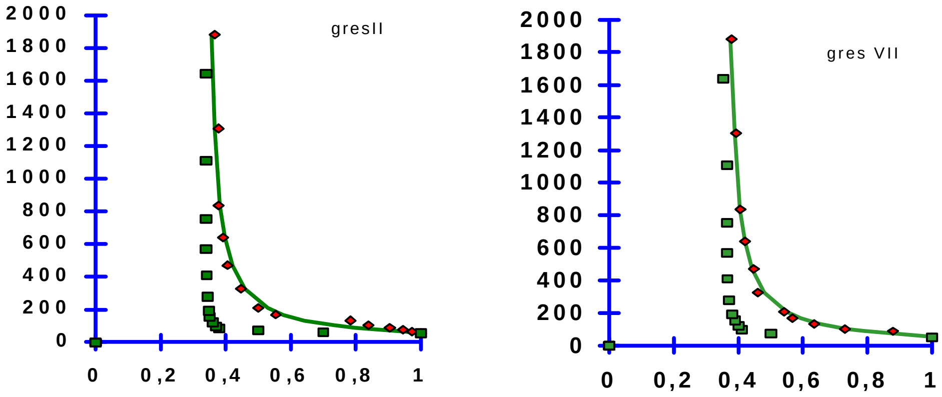

Figure 6 : Adjustment of core entry saturation (squares) versus mean saturation (diamonds), as a function of capillary pressure (mBar), using Forbes'algorithm

Simulation

To determine the correct RI versus Sw relationship, the influence of the saturation distribution in the electrodes region on the resistivity indices has been simulated.

The principle of the simulation is as follows: the volume of the sample is discretized in a grid (40x20x20), and the electrodes are featured as specific meshes, between which a ΔV is applied. The intensity of the current depends on the conductivity, thus of the saturation, in each grid mesh. The saturation is derived from the Pc curve for local saturations for Gres 2, deduced from Forbes adjustment, and fitted with a power function. The conductivity / resistivity values are drawn from Archie relationship for different values of n.

The first step of simulation is done with a sample fully saturated with brine, in order to check the geometrical factor arising from the different settings of electrodes between longitudinal and radial measurements: the results show that the dimensions and positions of the electrodes must be clearly defined. The second step is done with saturation values derived from the mean/local adjustment, and calculated along the sample. The resistivity values are calculated as a function of the local saturations for several values of n, the Archie exponent.

Figure 7 shows the experimental resistivity index as a function of the local saturation at the entry, the local saturation at the middle of the samples where the electrodes are located, as deduced from Forbes adjustment, and the experimental mean saturation (already shown in figure 5). At the beginning of the experiment the variation of saturation at the entry is quite large, without being « seen » by the electrical device : the RI remains low. At the electrodes level, the saturation is not yet modified while the RI is already enhanced. The mean saturation averages these effects, weighted by the variation of the saturation within the volume.

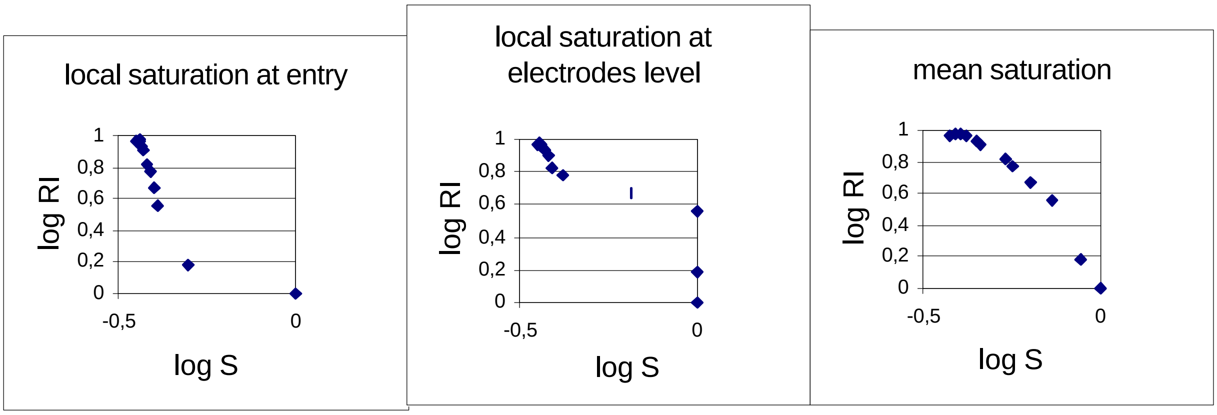

Figure 7 : Experimental values of resistivity index as a function of mean or local saturation (gres2).

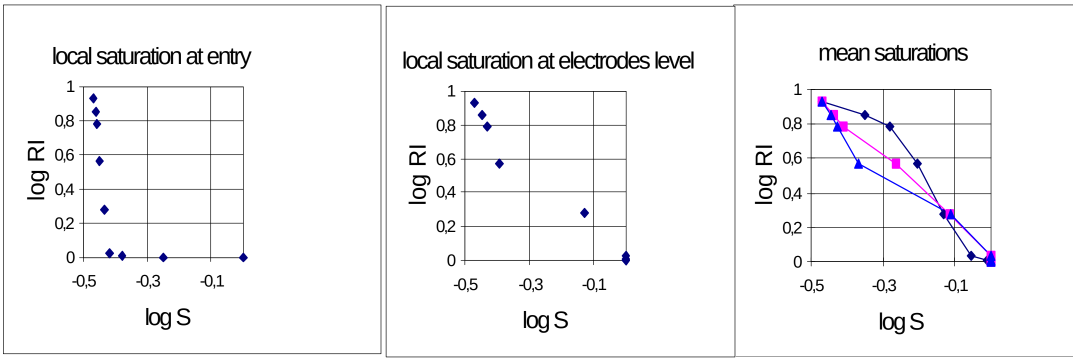

Figure 8 : Simulation of resistivity index vs local saturation at entry, local saturation at the electrodes level, and for mean saturation in thick slices centered at the electrodes level.(triangles : 36 mm, squares : 106 mm, diamonds : 240 mm thickness)

Figure 8 shows the calculated resistivity index for a value of n = 2 as a function of saturations derived from the fitted Pc curve : local saturation at the entry, or at the electrodes level, and mean saturation for different thicknesses of slice at the electrodes level. The experimental and simulated values have very similar shapes. The shape of the curve corresponding to a mean value for a slice thickness 240 mm, i.e., about half the volume of the core, is quite close to the experimental value, meaning that with this array of electrodes versus sample most of the electrical signal passes through this portion of the core volume. This is consistent with the experimental geometrical factor calculated from cores of the same shape and dimension (figure 3).

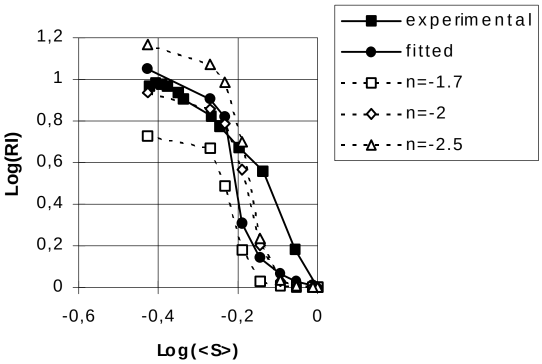

Figure 9 : Comparison of experimental (gres II) and fitted relationships between RI and Sw, and of simulated relationships, for different values of n, as calculated from simulation.

Figure 9 shows the experimental curve compared with the one deduced from the fit of the local Pc / saturation, and with the calculated mean curves for different n values. The fit is not absolutely good for experimental values at the beginning of the drainage, where the Pc are low, and the adjustment is not well constrained. It is better for the fitted curve. For the values close to Swi, the fit is quite good for both experimental and fitted curves with the simulation with n = 2. The end points are the same.

Some work remains to find a better fit, but up to now the results of the approach demonstrate that the curved shape of the experimental curve is actually due to the distribution of local saturations, and that the end points can be used to determine the n exponent.

Reservoir rocks

Reservoir rocks coming from the oil zone of a North Sea field have been drained according to the same procedures. Results are presented in figure 10 and 11. CAR1 has already been studied and determined as oil wet (Durand et al., 1994, 1997a,b), while 3445 is close to samples already determined as mixed wet. The values of resistance are higher than in Vosges sandstone, the values of mean Swi are lower, the values of RI vs <Sw> show also a curved shape, but the end points provide a higher value for n, which is consistant with the expected behavior. Further work will provide more precise interpretation.

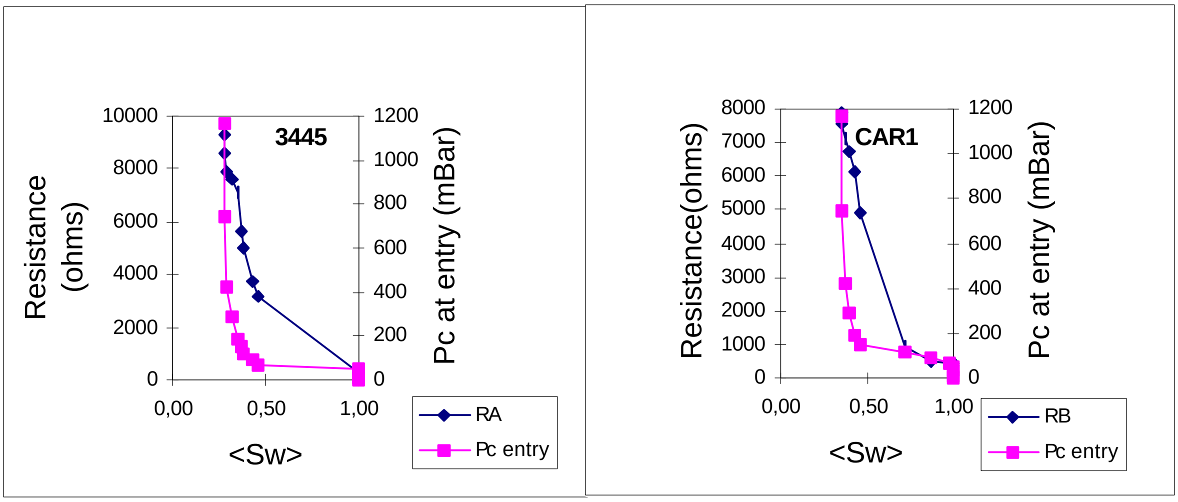

Figure 10 : Capillary pressure at entry and measured resistance for two reservoir rocks

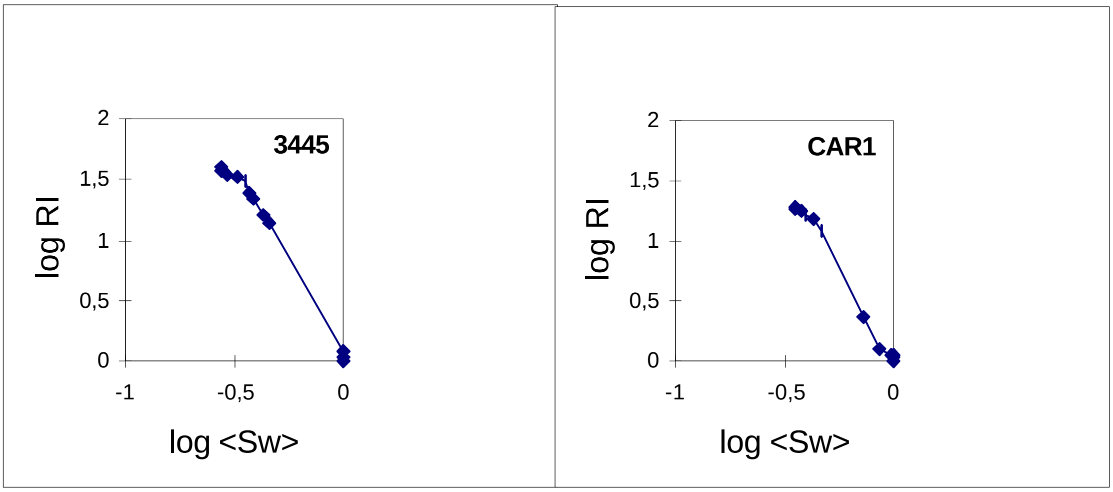

Figure 11 : Resistivity index as a function of mean saturation for two reservoir rocks

Conclusions

Measurement of resistivity indices while centrifuging is possible with the described device. Problems of weight, tightness and transmission of current have been solved. The reproducibility of experiments on model sandstone is fairly good. Consistent measurements of capillary pressures, mean and local saturations and resistivity are obtained. The simulation explains the shape of the resistivity index curve as resulting from the local saturation distribution. This explanation is consistent with the qualitative behavior, and with other displacement experiments. Determination of Archie exponent is thus possible, at least by successive approximations. Further work will allow a better relationship adjustment.

The experimental device can be used in imbibition as well as in drainage. The simulation procedure can be applied to the determination of Archie exponent, thus of saturations. It can contribute to the understanding of the effect of wettability and other properties linked to the distribution of minerals and pores at the core scale.

Application to reservoir samples is already begun and appears consistent with the expected behavior.

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