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FRIM: A FAST RESISTIVITY INDEX MEASUREMENT METHOD.

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Abstract

Measurements of electrical conductivity of core samples as a function of saturation are usually combined with porous-plate type capillary pressure measurements. Other methods for changing the saturation of the sample (centrifuge, flooding) have proven difficult to interpret due to the extreme sensitivity of the electrical measurements to the saturation profile. We propose a method derived from porous-plate experiments for measuring the resistivity index curve of a sample (Ir) independently of the capillary pressure curve (Pc). In essence, this method has some similarity with the continuous injection technique but differ fundamentally in the way of measuring resistivity: (i) the radial resistivity measurement is much less sensitive to non uniform saturation profiles (ii) the entire sample is investigated during the electrical measurement.

We show experimentally that the order of magnitude of the time required to measure a continuous Ir versus Sw curve, vary from a few hours to a few days depending on the permeability of the sample (from 2000 down to 100 mD respectively). The drainage experiments are performed on small samples (2.5 cm long and 4 cm in diameter), with a radial measurement of resistivity and one semi-permeable filter at the outlet face. The procedure is similar to a porous-plate type experiment in which different pressure steps are imposed and the average saturation and resistivity are measured simultaneously. However, capillary equilibrium is not needed and one to three pressure steps are successively imposed.

The numerical simulations of the 'porous plate' displacement process and the resistivity measurements confirm that the method is not sensitive to saturation profile in intermediate to low water saturation. The behaviour at high water saturation is not well predicted because the displacement is dominated by a percolation process which cannot be represented by a model based on Darcy's laws. Influence of permeability and Pc curve of the sample, membrane thickness, saturation exponent n, imposed pressure step are also qualitatively studied by numerical simulations.

Introduction

Resistivity index measurements on plugs are necessary to accurately estimate water saturation from log data. Therefore, obtaining a fast and accurate technique for resistivity index determination has been the objective of many researchers in the past ten years. In the laboratory, three techniques are mainly involved in this determination, i) a technique for resistivity measurement near the frequency of the logging tool to be calibrated ii) a technique for de-saturating a sample iii) a technique for measuring the saturation in the volume investigated by the resistivity measurement. There are several combinations possible and a popular combination is to use multi-sample air-water 'porous plate' de-

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saturation technique, a two-electrode resistivity measurement technique and a simple calculation of average saturation by weight difference. This approach has proven to be strongly inaccurate and too dependent on the quality of the manipulation (De Waal et al., 1991); it is slow and it does not take into account possible wettability effect. However, the cost is low and drainage capillary pressure curves are obtained. To improve accuracy (not at constant cost) using the same principle, different solutions were found :

- perform measurements separately on individual samples to better control capillary equilibrium and therefore obtain uniform saturation profiles
- use a 4 electrode technique to avoid overestimation of resistance
- use a continuous injection technique to speed up the experiments when only the Ir curve is needed (De Waal et al., 1991)
- optimize the duration of the de-saturation process by using micropore membrane and by decreasing the length of the samples (Longeron et al., 1995, Fleury and Longeron, 1996).

However, when the Ir measurement is linked to the determination of capillary pressure curves, the duration of the experiments is very difficult to decrease.

Other de-saturation techniques such as the centrifuge can be selected and operated in a similar way as in the multi-sample 'Porous Plate' method described above. However, the use of the centrifuge has also been proven to be inaccurate due to the accumulation of two important problems related to the saturation profile and contact resistance. It is not recommended by Sprunt et al. (1990). Durand and Lenormand (1997) used the centrifuge technique with radial resistance measurements while spinning in a very different way; however, the measurements must be corrected at intermediate speeds, and the correction method is linked to the accuracy in the capillary pressure curve determination.

Due to the Archie relation between Ir and Sw ($Ir=Sw^{-n}$), measurements are very sensitive to saturation, an advantage for logging tools that can also be turned to an advantage in the laboratory, but at the expenses of cost. Indeed, one can also determine the saturation profile (e.g. during a flooding) and shorten the experimental time by using in situ local saturation monitoring with multiple electrodes (Jing et al., 1993, Gray et al., 1992).

We propose here to return to simplicity with a new method which does not need expensive measurements such as in-situ saturation monitoring while still being fast and accurate.

Experimental set-up

General description

The experimental set-up (Figure 1) is mainly composed of a special core holder cell in which electrodes are implemented around the sample, a high precision production measurement system, a 4 electrode complex impedance meter, a data acquisition system.

The special core holder is described in the next section. The production measurement system is a low cost capacitive based detector with a precision of 0.05 cc and a resolution of 0.01 cc. (for details, see Fleury et al., 1997). The RLC meter measures the real and imaginary parts of the complex impedance of the sample. For all the experiments presented here, the imaginary part (related to capacitive effects) was always negligible compared to the real part (resistance) except at the highest frequency available (100 kHz). For all the experiments, we scan and record the complex impedance at 4 frequencies (0.1, 1, 10 and 100 kHz). For the present work, the resistance R at various saturation, Sw, is deduced from the real part of the signal at 1 kHz and the resistivity index Ir=R/Ro where the resistance measured in the cell at 100 % saturation, Ro=R(Sw=1).

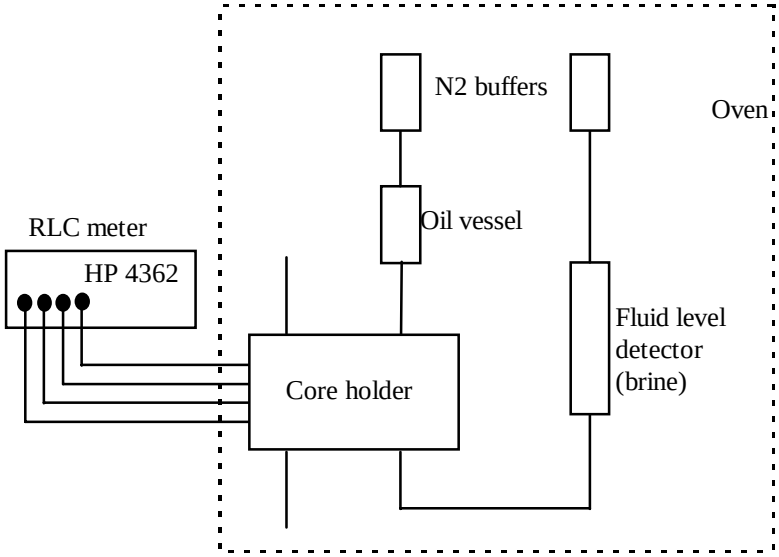

Figure 1: Schematic of the experimental set-up. Complex impedance at several frequencies, fluid level (brine production), oil and brine pressure, and temperature are recorded using a data acquisition system. The oven temperature is regulated within 0.2°C.

The CAPRIWET cell

The cell used can measure simultaneously capillary pressure and resistivity index curves. It cumulates two designs :

- a radial resistivity measurement system composed of 6 electrodes located around the sample (Figure 2). This design has been validated extensively in Fleury and Longeron (1996). The 6 electrodes are molded into the sleeve and are made of monel. They are connected to a 4-electrode type impedance meter (Figure 1), where two pairs are connected together (C- and C+, Figure 2). The electrodes are square shaped with a height of 10 mm to minimize short-cut effect occuring at the faces of the sample, as discussed in Fleury and Longeron (1996). The extension of the electrodes around the sample is not exceeding 90° for a pair of current electrodes. In addition, the high radial confining pressure (60 Bar) provides a good electrical contact between the electrodes and the sample. Hence, in normal conditions, contact resistance are usually of the same order of magnitude as the resistance of the sample to be measured at low water saturation.

- a cell with a U-shaped confining sleeve where membranes or ceramics can be inserted between the end-pieces and the sample (Figure 2). In the method presented here, we do not measure the capillary properties although the cell has such a capability (see Fleury et al., 1997). However, semi-permeable filters are still necessary to provide a particular saturation profile in the core sample, as described below. An advantage of semi-permeable filters is also that the average saturation is easily determined and is weakly dependent on the dead volumes of the end-pieces. This is of importance because the sample is small (40 mm in diameter and 25 mm in length) and pore volumes are of the order of 10 cc only.

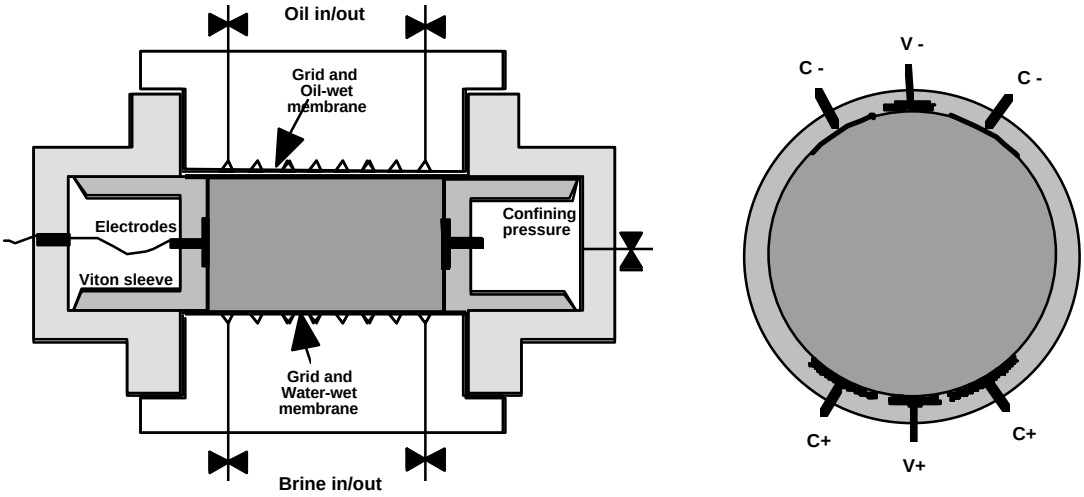

Figure 2: Schematic of the cell used. The size of the sample is 40 mm in diameter and 25 mm in length. A confining pressure of 60 Bar is applied. The six electrodes are molded into the sleeve. The cell is connected to a high precision volume detection system and to an impedance meter. Thick ceramics can also be mounted using different end-pieces.

The cell can be equipped with different types of semi-permeable filters (membranes and porous ceramics) and the use of membranes is not essential in the method presented here, as explained later. For determining the Ir curve in drainage, it is necessary to have a water-wet filter on the water side and for usual samples, a high entry pressure is not necessary. Indeed, the Ir curves is mainly determined by the variation of saturation in the plateau region of the capillary pressure curve and the variation of saturation in its asymptotic part does not provide much additional information. There are however some particular cases where the saturation exponent may increase at low water saturation due to oil wetting tendency or to complex porous structure (e.g. Herrick and Kennedy, 1996).

Experimental results

Experimental procedure

The experiments performed are oil-water pressure imposed displacement processes which are very simple to operate. However, the preparation of the sample must be carefully executed and is a key for successful experiments when membranes are used. In particular, the faces of the sample must be as flat and parallel as possible and prepared with a turning machine. Once the fully saturated sample is installed in the cell and all the tubes and end-pieces saturated with oil or brine, a membrane leak test is performed during 12 hours at 4 Bar and the temperature is stabilized during 12 hours.

The water pressure is maintained constant at about 2 Bar and the oil pressure is increased up to the desired value (defining a pressure step denoted Ps). We correct the saturation data for the small dead volume (about 0.1 cc) of the grid between the end piece and the sample on the oil side. We also correct the resistance of the sample at 100% saturation because there is a small variation of resistance when the oil is injected at the upper face of the sample. These precautions avoid any shift of the Ir curve near the origin (Sw=1, Ir=1).

Results

We show two membranes experiments performed with two samples of very different permeabilities (a Vosges sandstone of 80 mD and a synthetic core of 2400mD). The fluids used are brine (20g/l NaCl) and Soltrol 130. For the first sample, three pressure steps were successively imposed (Ps=100, 200 and 500 mBar) but equilibrium was only obtained at the first step, as indicated by the production curve (Figure 3, upper panel). For this type of sample, the capillary pressure of the plateau region is located around 100 mBar. When the resistivity index is plotted versus the average saturation (Figure 3, lower panel), we observe that the continuous curve obtained is closely fitted by an Archie type relation over the whole saturation range covered. Near Sw= 0.45, the fact that capillary equilibrium is reached has no effect on the Ir curve. The local deviation from a power law are best seen when the local slope n=-ln(Ir)/ln(<Sw>) is plotted as a function of saturation (Figure 3, middle panel) : n is slightly overestimated in the range 0.6-0.9 where the production is very fast.

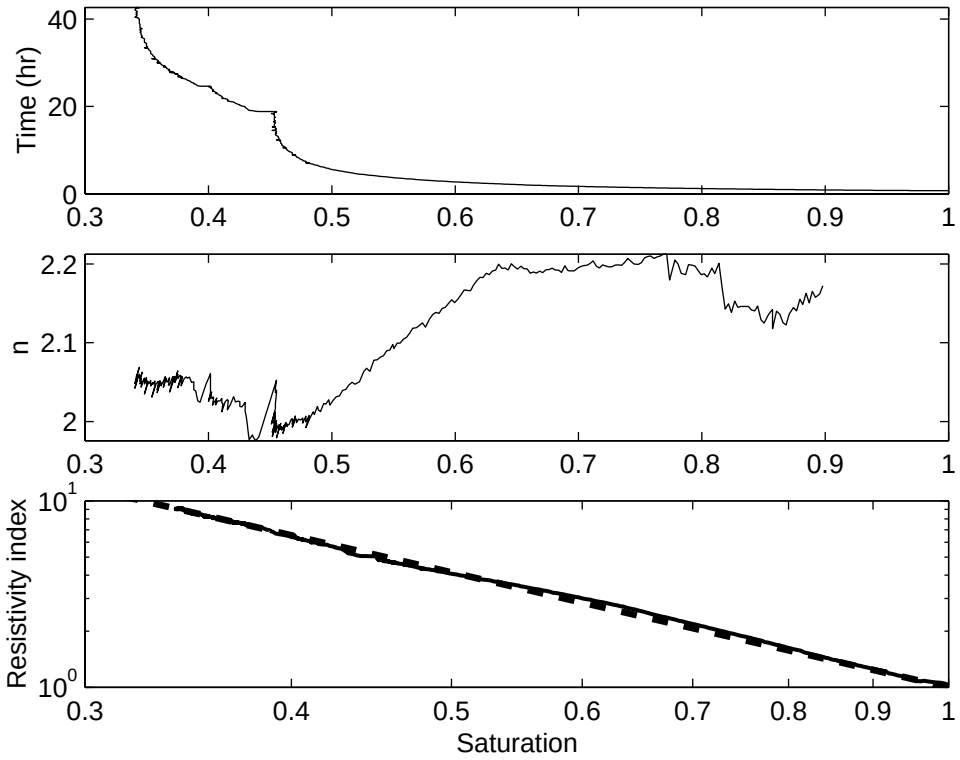

Figure 3: A continuous resistivity index curve for a sandstone (K = 80 mD) is determined in about 42 hours. Three pressure steps were successively imposed (100, 200 and 500 mB), as indicated by the breaks in the production curve (upper panel). The local slope n is defined by -log(Ir)/log(Sw) (middle panel). The resistivity index curve (lower panel) is best fitted by n=2.05.

In the second example (Figure 4), the duration of the experiment is much shorter (2 hours) due to the high permeability of the sample. We also applied only one step of pressure (Ps=450 mBar); compared to the first case, Ps is much higher than the pressure of the plateau region (around 30 mBar). Again, the Ir curve is well described by a power law over the whole saturation range from Sw=1 down to 0.18 (Figure 4, lower panel). The plot of the local slope (Figure 4, middle panel) indicate an underestimation of n in the high water saturation region (Sw=0.6 to 1).

The experimental results indicate that the resistivity index measurements can be performed in a very short time, from hours up to tens of hours depending on the permeability of the sample, without the need for capillary equilibrium. Ir curve are determined with a high precision and are surprisingly insensitive to the saturation profiles in most of the saturation range. A strong single pressure step yield more deviation than 2 or 3 steps at high water saturation but still provide a good accuracy at low water saturation.

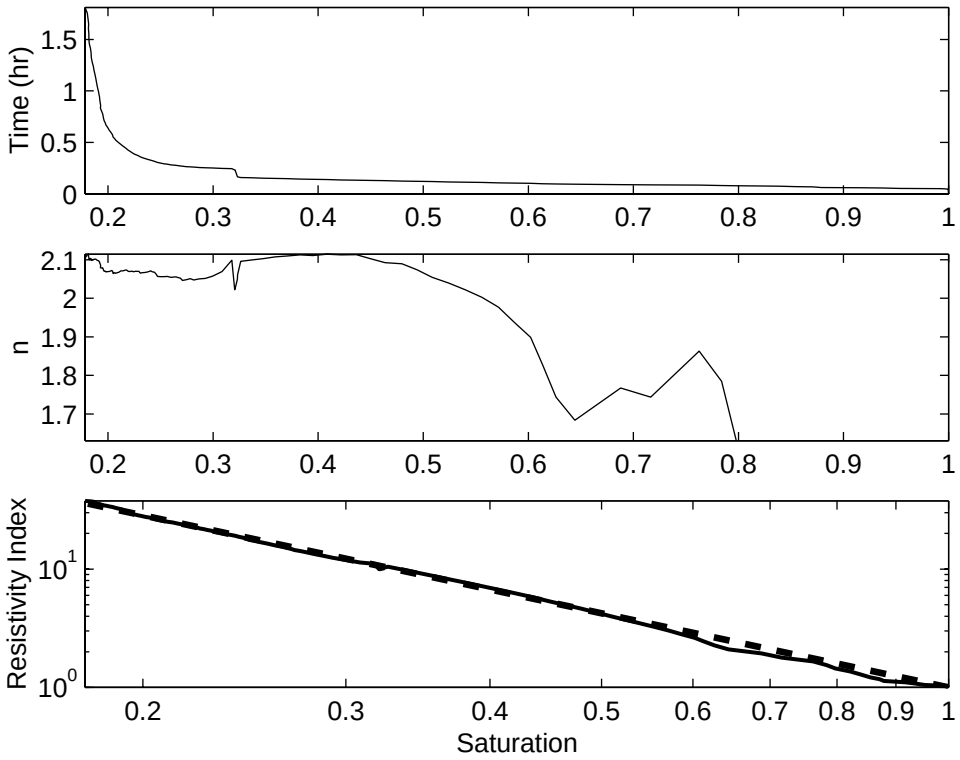

Figure 4: Same as Figure 3 but for a synthetic porous medium (2400 mD). The duration of the experiment is reduced to about 2 hours. A single pressure step of 450 mD was applied and the break in the production curve (upper panel) is due to a data acquisition problem with no effect on the Ir curve. The resistivity index curve is best fitted by n=2.08.

Interpretation

We performed numerical simulations to understand the virtual insensitivity of the resistivity measurements to non-uniform saturation profiles. There are two types of simulations :

- one dimensional numerical simulations of 'Porous Plate' displacement processes to calculate the saturation profile for a given set of capillary pressure and relative permeability curves. The simulator used was developed specifically for 'Porous-Plate' type experiments and has been used by Lenormand and Delaplace (1996) to demonstrate that relative permeability curves are poorly determined when using 'Porous-Plate' production data,
- three dimensional simulations of the electrical field to reproduce the variation of resistance between different profiles. Based on the analogy between electric field at low frequency and incompressible monophasic flow, we used a reservoir simulator (SARIP) in the same way as in Fleury and Longeron (1996) to calculate resistivity index. Current electrodes are represented by 4 wells with the adequate number of perforations working at an imposed pressure difference (2 producers and 2 injectors) and their geometry is as close as possible to the experimental situation (Figure 2). In addition, the high

conductivity at the lower face of the sample due to the water-wet membrane, and the small conductivity of the upper face of the sample due to the presence of oil (or the oil-wet membrane) is also reproduced by high and small permeabilities respectively. The total number of cells used is 20x20x40 respectively in the x-y-z directions.

For the simulations presented in Figure **5**, the following boundary conditions or parameters were imposed:

- a sample permeability of 100 mD
- a capillary pressure taken from other measurements on companion plugs (Figure **5**, right panel)
- an arbitrary set of relative permeability curves of the Corey type with both oil and water exponent equal to 3, and Kro(Swirr)=0.8
- a water wet membrane located at z=2.5 cm (Figure **5**) of thickness 0.1 mm and
- permeability 0.1 mD (typical values taken from tests)
- oil is injected at z=0 at three different pressures (165, 1000 and 2000 mBar)
- a saturation exponent n=2.

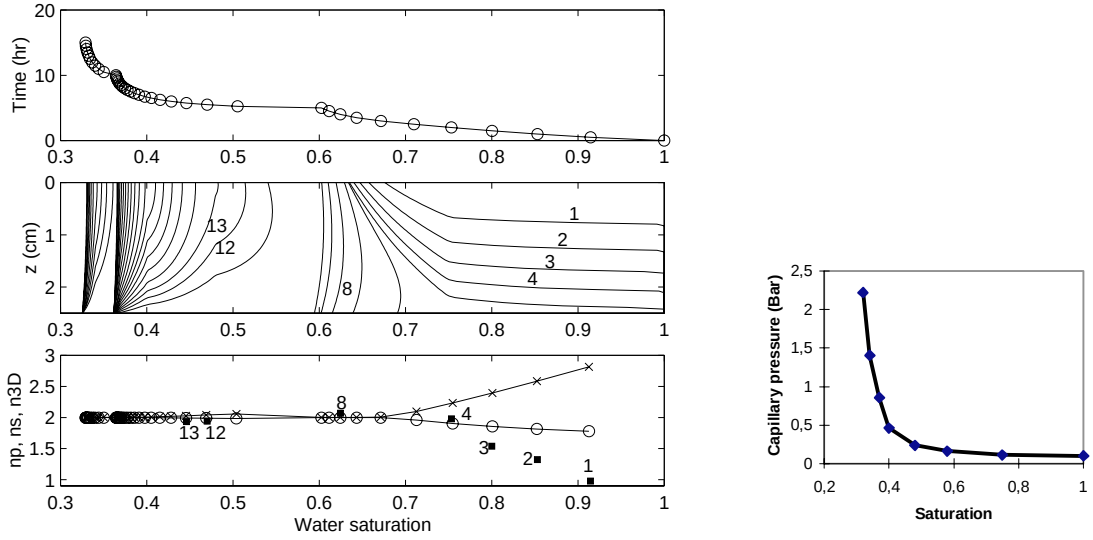

Figure 5: Simulations of the production curve (left upper panel), saturation profiles (left middle panel) and saturation exponent n using different models (left lower panel) during a 'Porous Plate' displacement. For the left lower panel, cross: ns model in series, circle: np model in parallel, squares: n3D from 3D simulations. The right panel indicate the capillary pressure curve used in the simulations. Oil is injected at z=0, a water wet membrane is present at z=2.5 cm.

For a given saturation profile (numbered 1 to 13), three saturation exponents $n=-\ln(R/Ro)/\ln(\langle Sw(z)\rangle)$ are calculated :

- np (model in parallel): each point of the saturation profile Sw(z) is a resistance with a value $R(z) = Sw(z)^{-n}$; the average resistance in parallel is $R = Rp = 1/\langle 1/R(z)\rangle = \langle Sw(z)^n \rangle$; this model should describe the measurements using radial electrodes

- ns (model in series): the average resistance in series is $R=Rs=\langle R(z)\rangle = 1/\langle Sw(z)^{-n}\rangle$; this model should describe measurements from face to face.
- n3D (3D analogue reservoir model) : the resistivity index Ir=Qo/Q where Qo is the reference flow rate calculated for a uniform saturation Sw=1. Q is calculated for a permeability profile $K(z) = Sw(z)^n$.

When analyzing the saturation profiles (Figure **5**), two domains should be distinguished :

- a domain at high water saturation (roughly in our case Sw=0.7 up to 1) where the simulations indicate that the oil has not reached the membrane. This domain is more dominated by a percolation process which cannot be reproduced with a simulator based on Darcy's law.
- a domain at intermediate and low water saturation (Sw<0.7) where the oil saturation can be larger at the outlet end (membrane side, z=2.5 cm) than at the inlet z=0 (e.g. saturation profile 12). This effect is due to the low pressure drop of the membrane allowing a fast de-saturation near the outlet and is also dependent on the choice of Kr curves.

From the simulations, we conclude that:

- by comparing ns, np and n3D (Figure **5**), a resistivity measurement design sensitive to the parallel mode is much less influenced by non-uniform saturation profiles. Because of the radial electrode geometry, this is essentially the case in our measurements. The 3D calculations indicate the same trends: n3D is very close to the input value n=2 for Sw<0.8.
- it is important to measure the resistance of the entire sample; indeed, for a large number of profiles, ns and np are close because $1/\langle Sw(z)^{-n}\rangle$ or $\langle Sw(z)^n\rangle$ are not very different from $Sw(z)^n$. Therefore, usual overestimation of n (Lyle, 1989) are not observed.
- at high water saturation (Sw>0.8), the simulations indicate a much greater sensitivity to saturation profiles: n3D is decreasing from 2 down to 1 (Figure **5**) far from the parallel model and in contradiction with measurements. There are two explanations: i) the electrical field is severely modified by the saturation profile and the parallel model cannot be applied ii) the simulations do not reproduce the percolation process occurring at high Sw and fingering features are more representative of the three dimensional oil distribution in the porous medium; therefore, the calculated saturation profiles are not relevant.

Effect of important parameters

When non equilibrium measurements are performed, the results are potentially affected by:

- the n value : when n is closer to 1 (clay rich sample, complex porous structure), the parallel mode compensates even more for non uniform saturation profiles; at the limit n=1, np=n for any profile. When n is increasing above 2 (oil wettability effect), the small effect of non uniform saturation profiles will be amplified,

- the choice of the pressure steps: based on numerical simulations and experiments (not shown), it appears that two pressure steps should be an optimum to minimize the duration of the experiments while keeping sufficient accuracy. When using membranes, the first pressure step can be chosen so that the saturation that would be obtained at equilibrium lie in the plateau region; such a pressure can be deduced from mercury injection measurements. A continuous increase of pressure steps does not provide more accuracy in less time.
- K and Kr values: these parameters will influence essentially the duration of the experiment and to a smaller extent the saturation profiles. However, the usual link between capillary pressure and permeability yields a duration roughly proportional to $\bar{K}^{1/2}$, when pressure steps are scaled to capillary pressure.
- the wettability of the sample: there is no particular effect related to wettability. In the case of spontaneous drainage (strong oil wettability), the pressure steps should be decreased to avoid strong non uniform profiles

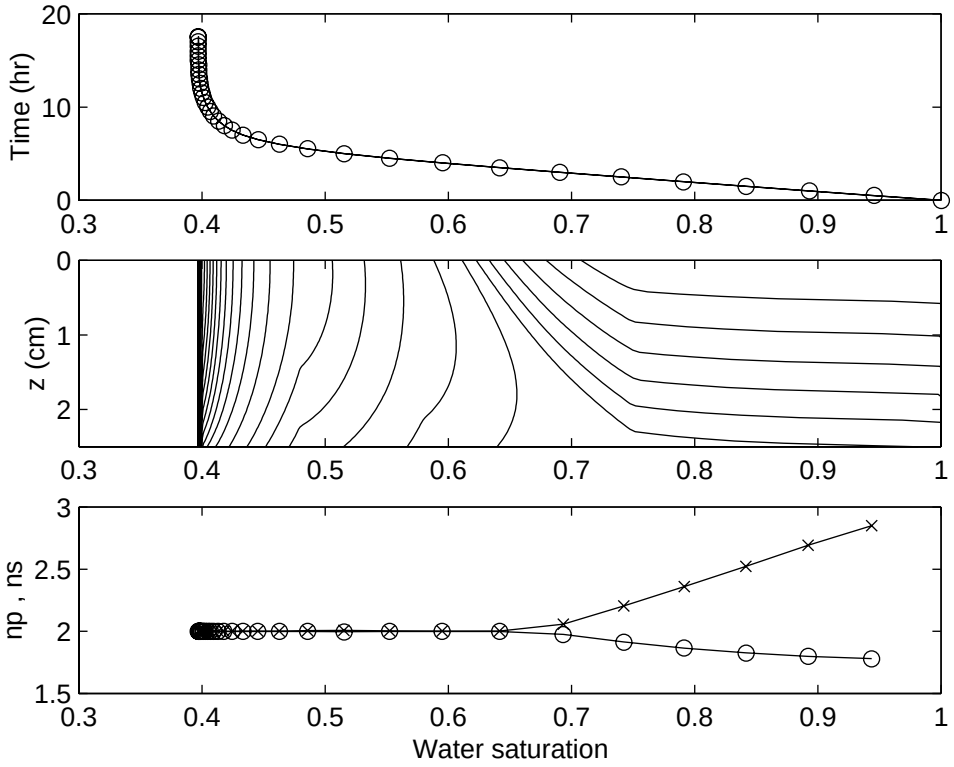

Figure 6 : same as in Figure 5 but using a ceramic filter of thickness 2 mm instead of a membrane. A single pressure step is applied at 500 mBar. In these conditions, the duration of the experiments is similar without loss of accuracy.

- the thickness of semi-permeable filter: actual membrane pressure breakthroughs are limited compared to porous ceramic and therefore, it is of interest to test the effect of thick ceramics. With a similar breakthrough pressure, ceramics will increase considerably the experimental time compared to membrane for the same pressure step.

However, Ps can be increased to compensate for the larger pressure drop of the ceramic. This is shown in Figure 6 where the simulations predict that neither the duration nor the accuracy of the experiment will be altered under these conditions. Indeed, np is close to the input value of 2 in a similar way than in Figure **5**. Note that the larger pressure drop of the ceramic modifies the shape of the saturation profile to a more uniform one (expected smoothing effect).

Conclusions

A new method (FRIM) for measuring resistivity index curves in drainage is presented. It requires a special cell with a radial electrode implementation and the measurements of the average resistance and saturation of the sample. We show experimentally and numerically the following aspects:

- a continuous resistivity index curve in drainage can be measured accurately in a short time (about 2 days for a typical 100 mD sandstone). This is less than the typical duration in the continuous injection technique (15 days) or other methods,
- the method is not linked to capillary pressure equilibrium,
- despite the fact that non uniform saturation profiles are present during the measurements, their impact is negligible. This is due to a combination of i) the radial resistivity measurement technique ii) the presence of semi-permeable filters at the outlet end, iii) the fact that the entire sample volume is investigated by the electrical measurements (this is verified when the sample diameter is larger than the length).

Future work will focus on the resistivity index curve during imbibition and the study of the effect of frequency. For imbibition, preliminary tests indicate that the Ir curve can be obtained by imposing a single pressure step down to negative Pc value in similar experimental time than in drainage.

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Nomenclature

Ir	resistivity index R/Ro
n	local saturation exponent such as $Ir=S^{-n}$
np	saturation exponent $np=\ln(Ir)/\ln(\langle Sw(z)\rangle)$ where Ir=Rp/Ro
ns	saturation exponent $ns=\ln(Ir)/\ln(\langle Sw(z)\rangle)$ where Ir=Rs/Ro
n3D	saturation exponent calculated with 3D electrical field simulations
Q, Qo	flow rate, référence flow rate
Ps	pressure step, imposed pressure difference between oil and brine
Rp	average resistance in parallel, $Rp=1/\langle 1/R(z)\rangle = \langle Sw(z)^{n}\rangle$
Rs	average resistance in series, $Rs=\langle R(z)\rangle = 1/\langle Sw(z)^{-n}\rangle$
Sw	local water saturation, function of z

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