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COMBINED RESISTIVITY AND CAPILLARY PRESSURE MEASUREMENTS USING MICROPORE MEMBRANE TECHNIQUE.

M. Fleury and D. Longeron

Institut Français du Pétrole

Abstract

Capillary pressure measurements using water and oil wet micropore membranes can be combined with four electrodes resistivity measurements in a simple apparatus. Such a device can improve significantly resistivity log interpretation while providing data for reservoir simulations. The originality of the device is that resistivity is measured using current and potential electrodes located around the sample as in electrical tomography. To speed up capillary pressure measurements with thin semi-permeable membranes, the sample must be short (e.g. 2.5 cm) while having a large diameter (e.g. 4 cm) to minimise saturation measurement errors. Hence, the classical implementation of the electrodes on the faces and around the sample is technically very difficult for various reasons. In the design presented, the electrodes do not interact with the membranes and the determination of resistivity is possible in any capillary pressure cycle, whether or not one face is saturated with oil.

The method is validated using results from experiments and numerical simulations. Combined capillary pressure and resistivity measurements on a water-wet outcrop sandstone indicate a single value of saturation exponent in drainage and imbibition and a very good correlation of the data point in log-log scale. When a 2-electrode technique is used, experimental data indicate also that contact resistance can lead to severe artefact of measurements such as the appearance of a hysteresis between drainage and imbibition. Numerical simulations of the electrical field were performed to test the design of the electrodes and optimise their size. It is shown that a large part of the sample contributes to the measurements and short cut due to conductive end pieces do not affect the results.

Introduction

Knowledge of the water-oil capillary pressure and resistivity index vs. saturation relationship is necessary for many reservoir engineering tasks like: (1) assess connate water saturation to calculate oil-in-place; (2) calibrate resistivity logs; (3) determine the height of the transition zone; and (4) model oil displacement either by free water imbibition and /or water injection.

Capillary properties of core samples are difficult to measure and the experiments are usually time consuming. In recent years, progress has been made in restored state experiment by using micropore membranes (Jennings et al., 1985, Hammervold et al. 1992, Longeron et al. 1995). The experiments can be about ten times faster and full cycle of capillary pressure can now be obtained in a reasonable time. Electrical properties are also difficult to measure properly (Sprunt et al., 1990). It is often desirable to scan the entire saturation range (from irreducible water saturation up to residual oil saturation) because resistivity index vs. saturation relationship are sometimes complex (presence of clays, conductive matrix, etc.). There is also growing experimental evidence that the saturation exponent is different in drainage and in imbibition when non water wet reservoir samples are considered. Hence, experimental data are needed to interpret resistivity log in water flooded reservoir zones (Maute, 1992). Combining capillary pressure and resistivity measurements is therefor necessary to provide high quality information.

Background

Micropore membrane technique:

Restored state experiments are time consuming and researchers have developed various methods to obtain faster the results while keeping the same representativity. In standard methods, a thick semi-permeable porous ceramic disc is in capillary contact with a sample (fig. 1). To reach capillary pressure of the order of 2 Bar with oil-water systems, the disc has small pore throats (of the order of 0.1 μm) and thus, a very low permeability. From this starting point, there are mainly two ways to speed up the experiments: increase the total permeability of the system (sample + semi-permeable filter) and/or, perform the experiment at a constant injection flow-rate (Kokkedee and Maas, 1994) instead of a constant pressure difference (usual method).

The total permeability can be increased by using thin membranes, providing the major impact on time saving. For example, the total permeability of a sample having a membrane at one face (fig. 1) is determined by the length L and permeability K of each porous media:

$$\frac{L}{K} = \frac{L_s}{K_s} + \frac{L_m}{K_m}$$

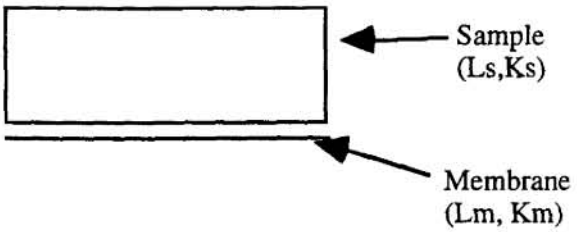

Figure 1: Schematic of a restored state experiment. In standard system, the membrane is a ceramic disc (thickness of a few millimetres)

When using micropore membranes (L_m = 0.1 mm) instead of porous ceramic discs (L_c = 5 mm), the total permeability K is increased by a factor larger than 300 when taking a typical sample permeability of 100 mD (and length 2.5 cm) and a typical membrane/ceramic permeability of 0.1 mD (note that only the ratio L_m/K_m has a meaning when considering membranes) . In addition, experiments will also be faster when using short samples because the equilibration time is proportional to the square of the length (Jennings, 1985). As a compromise, we chose a length and diameter of 2.5 and 4 cm respectively, to keep a pore volume sufficiently large to minimise volume measurement errors.

Combined resistivity measurements:

Standard resistivity measurements are performed using 4-electrode technique as shown in fig. 2. To measure correct values of resistance, potential must be measured using separate electrodes to avoid contact resistance between the electrodes and the sample. We show later that the contact resistance can be of the order of the resistance to be measured. Current electrodes are usually located at each face of the sample (fig. 2) and are used also as end-pieces for fluid injection.

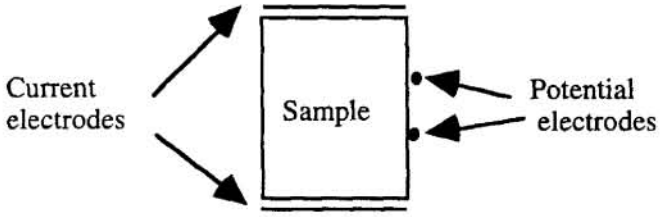

Figure 2: Conventional four electrode technique.

Using such a design on a short sample is difficult because current electrodes and membranes must be implemented together. Especially when an oil-wet membrane is used during forced imbibition, current cannot be injected easily. Conductive meshes and tissue paper can be used (Elashahab et al., 1995) but the preparation of the system becomes very delicate and measurements artefacts can be generated.

Electrode design

We propose a new electrode implementation derived from those used in electrical tomography (Barber and Brown, 1983) and from previous work (Lytle et al., 1979, Lewis et al., 1988). In our design, current and potential electrodes are located around the sample. The main advantage is to separate electrodes and membranes and therefor to permit resistivity measurements in any capillary pressure cycle and an easier manipulation.

We first tested our design using an epoxy coated sample in which 10 metallic screws were inserted around the sample (fig. 3). Some electrodes are used for injecting current and others to measure the potential at the surface of the sample. Various combinations can be imagined and we selected 4 different arrangements of current and potential electrodes (fig. 3):

- C1: current is passed between electrodes 2, 4, and 7, 9; potential is measured between electrode 3 and 8 (fig. 3).
- C2: same as C1 but potential is measured between electrode 1 and 10
- C3: same as C1 but potential is measured between electrode 5 and 6
- C4: current is passed between electrodes 1,2, 3, 4, 5 and 6, 7, 8, 9, 10; potential is measured between the same set of electrodes.

We present hereafter the measurements performed with the above combinations. C1, C2 and C3 are 4-electrode technique while C4 is a 2-electrode technique.

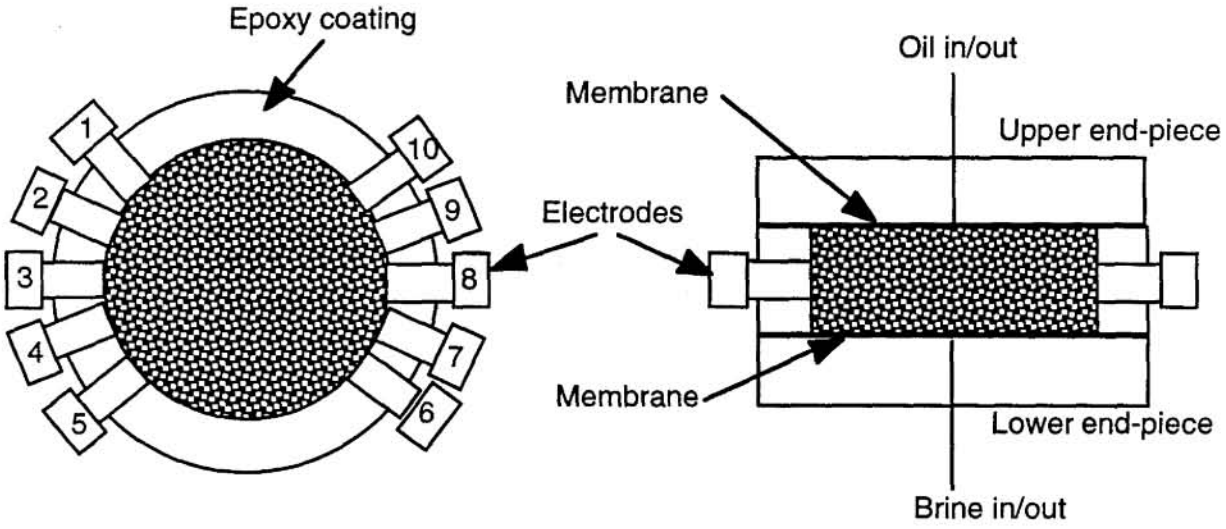

Figure 3: Validation of the method for measuring resistivity simultaneously with capillary pressure. Electrodes are screwed into the epoxy coating. Water wet and oil wet membranes are placed between the end pieces and the sample.

To change the saturation and obtain the capillary pressure curve, a water wet membrane was placed between the sample and the lower end piece. Then, oil pressure was increased step by step during drainage (9 steps) and decreased step by step during imbibition (8 steps).

Brine production was measured within ±0.02 cc accuracy (better than 1 % in saturation). At equilibrium (no production), the resistance from the various combinations C1 to C4 were determined at a frequency of 1 kHz and a maximum voltage of 1 V. The sample used was an outcrop sandstone (Grès des Vosges) with the following characteristics: permeability 80 mD, porosity 22.5%, formation factor 11, diameter/height 40/25 mm. The fluids used were brine (20 g/l NaCl) and Soltrol 130.

For all the combinations, the different resistivity indices were determined during the same drainage-imbibition cycle using:

$$I = \frac{R_t}{R_o} = S_w^{-n} \quad \text{with} \quad R = \frac{\Delta V}{I}$$

The potential difference ΔV and the current I are measured in the different combinations C1 to C4. Note that the resistivity (RxS/L where S is a surface and L a length) cannot be determined easily. A "cell coefficient" (S/L) can be calculated using a medium of known resistivity.

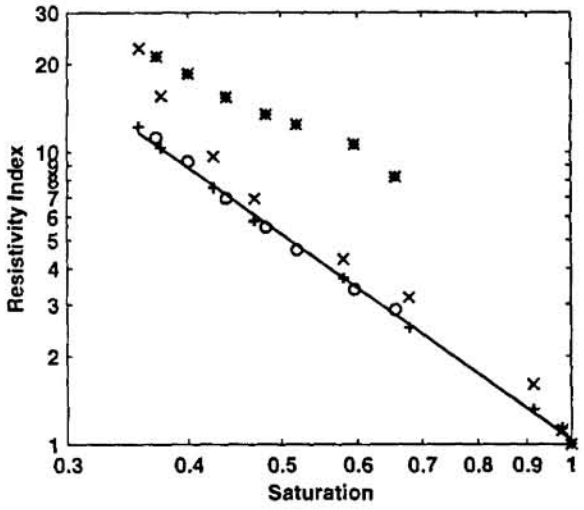

Figure 4: Resistivity index curve obtained with four and two electrodes technique. C1 combination (4 elec.): drainage (+) and imbibition (o); C4 combination (2 elec.): drainage (x) and imbibition (*).

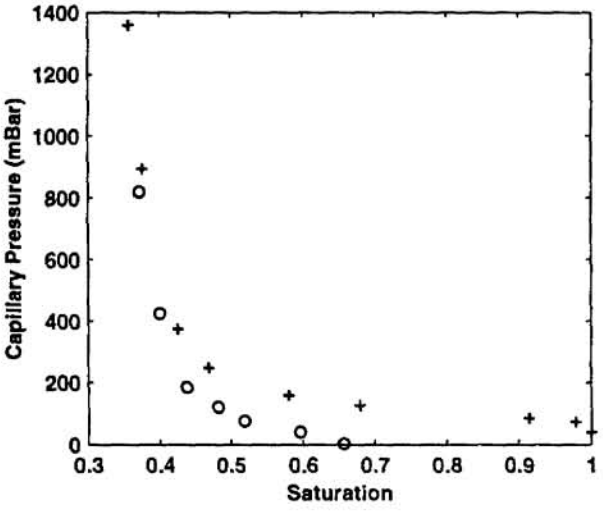

Figure 5: Capillary pressure curve obtained simultaneously with resistivity curve. Drainage (+) and imbibition (o).

When plotted in log-log scale, a unique power law is obtained for the resistivity index curve during drainage and imbibition with the combination C1 to C3 (4-electrode technique) (fig. 4, results for C1 plotted only). In comparison, when a 2-electrode technique is used (combination C4), a severe deviation from a power law is observed at low water saturation and

high capillary pressure (fig. 4 and 5). The explanation is that, at sufficiently high capillary pressure, the space between the electrode and the porous medium can always be filled with oil, although the contact is mechanically very good (electrodes are screwed and the sample is flat at the screw location). As a result, the resistance increases anomalously (contact resistance) and near Swi, the measured index from the 2-electrode technique is about twice as large as the one measured with a 4-electrode technique (R_0 being approximately equal, contact resistance can have the same amplitude as the sample resistance). When the water saturation is increased again (imbibition), the oil trapped between the electrodes and the sample is not completely evacuated. As a result, we observe an hysteresis between drainage and imbibition, which is purely a measurement artefact. These results validate the electrode design and indicate that a 4-electrode technique is necessary, as recommended by other authors (Lewis et al. 1988, Sprunt et al. 1990).

The results concerning the measured slopes (saturation exponent n) are summarised in table 1. For the 4-electrode techniques and independently of the position of the potential electrodes (combination C1 to C3), we find a power law in drainage and imbibition with a slope of -2.35. The larger slope (2.71, table 1) obtained for combination C3 during imbibition is not understood. For combination C4 (4-electrode technique), two different slopes are measured in drainage and imbibition (-2.7 and -1.5 respectively). For drainage, the increase of the slope is due to the data points at low water saturation ($Sw<0.4$, fig. 4).

Combination	Slope for drainage	Slope for imbibition
C1	-2.34	-2.41
C2	-2.34	-2.42
C3	-2.27	-2.71
C4 (2 elec.)	-2.73	-1.55

Table 1: Slopes in log-log scale for the resistivity index curve obtained from various combination of electrodes (see fig. 3). All combinations are 4-electrode technique except C4. C1 and C4 are plotted in figure 4.

Numerical simulations of the electrical field

We performed numerical simulations of the electrical field to:

- understand the electrical field generated by our non conventional electrode design
- identify possible unexplored regions of the sample
- determine some criteria for the size and implementation of the electrodes
- study the effect of conductive or non conductive end-pieces

Using the analogy between electrical field (at low frequency) and monophasique, incompressible flow, we used a reservoir simulator (SARIP ^{CH}) to calculate isopotential (or equivalently current lines). In this situation, there is a simple correspondence between the following quantities:

Current I	$\leftrightarrow$	Flow rate Q
Voltage drop ΔU	$\leftrightarrow$	Pressure drop ΔP
Conductivity σ	$\leftrightarrow$	Permeability K

Electrodes at the periphery of the sample are represented by horizontal wells which are constant pressure injectors or producers. As output, the simulator computes the pressure in each cell and the total flow rate between wells (current between electrodes). For 2D simulations (vertical or horizontal), the cell size correspond to 1x1x1 mm (i.e. there are 40x40 cells to represent the cylindrical sample of diameter 40 mm). For 3D simulations, the system was represented using 20x20x5 cells (including end pieces). The actual pressure drop and permeability K_0 used were 2 Bar and 10 mD but this choice is arbitrary and have no consequences on the results. The effect of electrical conduction of the end-pieces is simulated using layers above and below the porous media. Their permeability was either set to 0 or 100 D. Because the flow is incompressible, a stationary flow is obtained instantaneously and only one time step is necessary to perform the calculation.

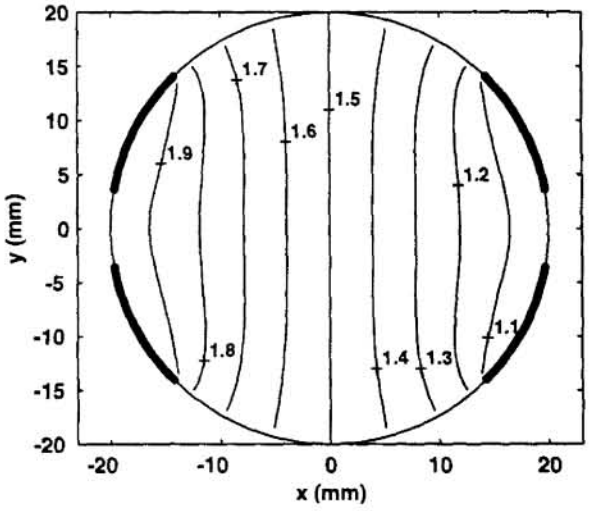

Figure 6: Isopotential obtained from 2D simulation of the electrical field (horizontal view). Current electrodes are represented by the thick lines; left and right electrodes have a potential of 2 and 1 respectively. The electrical field is fairly uniform using large electrodes.

From the simulations, we retained an electrode design as shown in figure 6 and 7. Viewing the electrical field from the top (horizontal slice), the current electrodes must be

relatively large (fig. 6) to insure a fairly homogeneous electrical field across the sample. Potential electrodes (not represented) are smaller and located between each pair of current electrodes (as in combination C1, fig. 3).

Viewing the electrical field in a vertical plane (fig. 7), we have also the choice of the vertical size of the electrodes. However, one should take into account the effect of the end-pieces that can be made of conductive and non conductive material. When the end pieces are made of conductive material, the electrical field is very different (fig. 7): more current is flowing near the edges of the sample than through the centre of the sample. However, in both situation, the measurements are possible if the height of the electrodes is not too large (e.g. 10 mm or , less than the half of the height of the sample), as shown in figure 7.

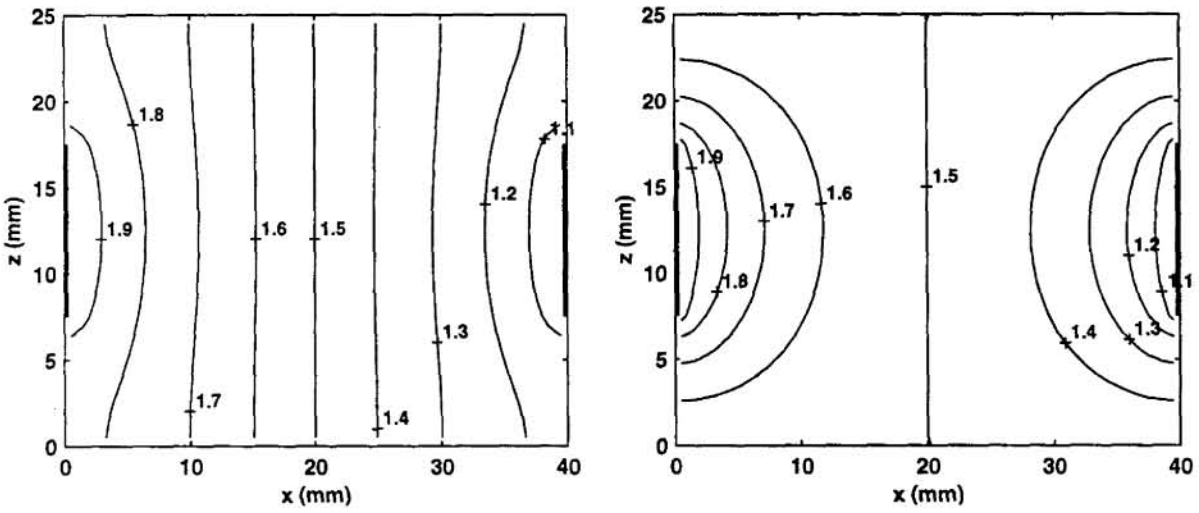

Figure 7: Isopotential obtained from 2D simulation of the electrical field (vertical view). Current electrodes are represented by the thick lines; left and right electrodes have a potential of 2 and 1 respectively. Two cases are presented: non conductive (left) and conductive (right) end-pieces (located at z=0 and 25 mm).

Using electrodes of the size indicated in figure 6 and 7, 3D numerical simulations indicate that the flow rate (i.e. current) is about 11 % larger when 1 conductive end-piece is used. Measurements on the sample indicate a current increase of about 18.5%, in rough agreement with the simulations. Thus, the "short cut" effect is not dominant. Moreover, the conductivity along the faces of the sample does not vary during the experiment due to the membranes. We also checked the effect of conductive end-pieces for various values of conductivity; when the conductivity is increased by a factor 10, the current is also increased by the same factor. In other terms, if Q_0 is the flow rate measured for a permeability K_0 (e.g. 10 mD), the equation $Q/Q_0 = K/K_0$ is verified when K is increased up to 1000 times K_0. In

conclusion, measurements with conductive end-pieces are possible but we recommend the use of non conductive end-pieces to obtain a more homogeneous field.

Conclusion

For relatively thin cylindrical core sample having a large diameter, capillary and electrical properties can be determined simultaneously by placing electrodes at the periphery of the sample while semi-permeable membranes are placed against the faces. This design has the advantage of separating electrodes and membranes for a simpler apparatus.

The experiments performed show that resistivity index vs. saturation relationship can be obtained without measurement artefacts due to contact resistance between the electrodes and the porous medium. Using the new design, a unique saturation exponent is found in drainage and imbibition with a very good correlation of the data points in log-log scale (water-wet sample). The results indicate also that a 2-electrode technique cannot be used at low water saturation even when the quality of the contact seems to be excellent.

Numerical simulations help understand the electrical field generated in the porous medium. When current electrodes are large enough, the electrical field is fairly homogeneous. The effect of conductive and non conductive end-pieces is not dominant when electrodes are properly designed and does not generate measurement artefacts.

Further development of this technique for the simultaneous measurements of capillary and electrical properties will be the design of a core-holder cell capable of handling preserved core samples with a controlled confining pressure and at temperature up to 90°C. Experiments are in progress to test the device.

Acknowledgements

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Nomenclature

L	sample length, cm
R_t, Ro	measured resistance at a given saturation , at Sw=1.
Pc	capillary pressure

Sw	average brine saturation
I	resistivity index = Rt/Ro
Subscript s, m, c	respectively for sample, membrane, ceramic
K	permeability, mD

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