

AN INTEGRATED PETROPHYSICAL TOOL MEASUREMENTS AND DATA INTERPRETATION

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Abstract

The Integrated Petrophysical Tool (IPT) is derived from the semi-dynamic method for capillary pressure measurement presented at the 1993 and 1995 Society of Core analysis meetings. The IPT simultaneously measures the following properties : complete oil/water capillary pressure cycle, resistivity index, end-points and parts of the relative permeability curves. The paper describes the methodology used to acquire and to interpret the data. Examples are given for two reservoir samples. The IPT is based on the steady-state injection of one fluid through the sample placed in a modified "Hassler" cell, equipped with pressure taps and electrodes. Local saturations are not measured but calculated from the effluent production using a combined analytical and numerical method. Measurements were performed at room condition with oil (Soltröl) and brine on sandstone reservoir cores. The whole cycle consisted in about 30 steps at various oil or water flow rates and took about four weeks for a 120 mD sample (1st drainage, positive and negative imbibition, 2nd drainage). Relative permeabilities agree with standard steady-state measurements and capillary pressures with centrifuge results for one sample. There is no comparison for resistivity index, but the results are in agreement with literature data. The main technical difficulty is the need for accurate determination of effluent production. For this purpose, several improvements are proposed. In conclusion, the Integrated Petrophysical Tool is as accurate as standard methods but has the advantage to provide the various parameters on the same sample and during a single experiment.

1. Introduction

The purpose of petrophysical measurement is to determine the capillary pressure (P_c) and relative permeability curves (K_r) as functions of saturation. In addition, electrical properties (formation factor and resistivity index I_R) are determined for the calibration of log data.

The petrophysical measurement methods have been developed over several years. However, there is still on-going research to improve not only the accuracy but also the speed and automation of measurements. One approach is to measure different parameters during the same experiment with the same sample ("integrated measure"). The purpose is not only to reduce cost but also to increase the representativeness by using the same sample.

In this paper, we first recall the integrated methods for measuring P_c and K_r curves. We then describe the original method developed for the simultaneous measurement of the three

properties : P_c , K_r , R . Finally, we present and discuss the results obtained with two reservoir samples.

2. Measurement of Petrophysical properties

In core analysis, there is a general trend towards the simultaneous determination of relative permeabilities and capillary pressure curves during the same experiment.

A few years ago, several studies (Richmond and Watson, 1988, Chardaire-Rivière, 1992) were devoted to the simultaneous determination of capillary pressure curves (P_c) and relative permeabilities (K_r) by automatic history matching during core flood experiments. It is now recognized that it is more accurate to measure the capillary pressure separately. However, the K_r functions can be derived using the transient of the production. Several papers have been published for the various methods. For the centrifuge method: OMeara and Crump, 1985; Nordtvedt et al., 1993; Nimmo, 1990 with local saturation measurements using resistivity. For the "porous plate" or "membrane" method: Jennings et al., 1985; Longeron et al., 1994; Christoffersen, 1995. In the membrane method, the transient is often used to estimate the equilibrium saturation (Guo and Hammervold, 1993). However, the method is not accurate due to the high hydraulic resistance of the membrane and the presence of the second fluid (Lenormand *et al.* 1996). A new method combines the membrane method and a continuous injection (Kokkedee and Boutkan, 1993; Kokkedee, 1994). With the membrane method, a simultaneous P_c and resistivity index is also available (Fleury and Longeron, 1996).

In order to design an integrated tool that can perform simultaneous measurements of the P_c and K_r curves and the resistivity index, we have looked at the drawbacks and advantages of the various methods :

- the porous plate and membrane methods are not suitable for K_r measurements.
- the centrifuge method cannot measure the positive imbibition and the negative drainage. In addition the method is limited for high pressure and temperature.

Consequently, we preferred use the semidynamic method for an integrated petrophysical tool (IPT).

3. The Integrated Petrophysical Tool (IPT)

3.1. Principle of the IPT

The semidynamic method allows the complete P_c cycle to be determined (Lenormand *et al.*, 1993, 1995). During the same experiment, it is also possible to determine parts of the K_r curves by steady measurement. In addition, resistivity indices are easily measured.

During positive capillary pressure measurements (Fig. 1), oil is flowing through the sample. Consequently, there is a direct measurement of permeability to oil provided that saturations are known. If we note S_0 the inversion point (corresponding to $P_c=0$ during imbibition), $K_r(\text{oil})$ is measured for $S < S_0$ and $K_r(\text{water})$ for $S > S_0$ (Fig. 2).

In this study, we used a cell with 6 pressure taps along the sample (Fig. 3). For electrical measurement, the current is injected through the end-pieces and tensions are measured using the pressure taps. The effluent volume, leading to the average saturation, is measured by an

accurate capacitance method in the tube separator. Local saturations at the entrance are calculated from the average saturation using the following method.

3.2. Calculation of the local saturation

The first version of the semidynamic method had the drawback of requiring saturation measurement at a few points along the sample. For this purpose, we used an ultrasonic technique, which is accurate but impossible to use with gas and difficult to incorporate in an automatic set-up. The problem has been solved by calculating the saturation from the average saturation. This approach is based on an analytical calculation that only use the entrance pressure and average saturation (Ramakrishnan and Capiello, 1991, Lenormand *et al.*, 1995). The principle of the calculation is to consider the series of experiments performed at different flow rates to derive the local water saturation S , corresponding at the entrance pressure Pe , from the average saturation $\langle S \rangle$

$$S(Pe) = \langle S \rangle + q_2 \frac{d \langle S \rangle}{dq_2}$$

For each flow rate, the entrance saturation $S(Pe)$, together with entrance pressure Pe gives a point on the Pc curve (since the pressure in water is taken as reference, $Pe=Pc$).

For Ramakrishnan and Capiello, the method was applicable mainly for relative permeability, since the average saturation is too difficult to measure experimentally. In this paper we will show that the capillary pressure curve can also be measured. We have tested this method using simulated data as well as real experiments with saturation measurement using a CAT scanner (Lenormand *et al.*, 1995).

4. Results

4.1. Procedure

Sample 1 and 2 are two reservoir sandstone cores of diameter 4 cm and length 8 cm. They are first cleaned with toluene and isopropanol to remove crude oil. Then, the samples are saturated with brine and the displacements are started at room conditions (20 C and exit at atmospheric pressure). The injection flow rates range from 5 to 1000 cm³/hour. The rate used for washing the outlet is always 20 cm³/hour. The duration for the whole cycle (primary drainage, positive and negative imbibition, secondary drainage) is about one month.

Table 1 Fluid and rock properties.

Rock samples		sample #1	sample #2
	porosity	0.22	0.22
	solid density (g cm ⁻³)	2.65	2.70
	water permeability (m ²)	0.125 10 ⁻¹²	1.19 10 ⁻¹²
Paraffinic Oil	viscosity (Pa s)	1.3 10 ⁻³	1.3 10 ⁻³
Brine	viscosity (Pa s)	1 10 ⁻³	1 10 ⁻³
	salinity (g/l)	120	25

4.2. Capillary pressures

Capillary pressure curves are first displayed using the average saturation: pressure difference between the two faces of the sample vs. average saturation (Fig. 4). The maximum capillary pressure is higher for sample #1 which is less permeable.

When capillary pressure is high, the variation in effluent production is not enough significant to give accurate average saturation in the core. Here we propose a method to extrapolate the average saturation from the points for which measurements are accurate, named "good points". First, a good fit for the average saturation $\langle S \rangle$ vs. $\ln(Q)$ is produced using a 2nd order or 3rd order polynomial (fig. 5). Then, the local saturation at the entrance is calculated from Ramakrishnan's equation. The corresponding "good points" of the capillary pressure curve are fitted using a power law (any other function could be used). The fitting parameter is the irreducible water saturation, S_{wi} . The "numerical" average saturation is then calculated using $P_{c,fit}(S)$ and the measured K_r using a 1D numerical simulation of the steady-state flow. The drainage P_c curves with local saturation and average saturation and the extrapolated curve with average saturation are presented in Fig. 6. The shapes of the P_c curves show that both samples are water-wet.

4.3. Electrical Properties

We first measured the formation factor when the samples are saturated with brine.

sample #1 : FR=18.9; Archie exponent $m=1.94$

sample #2 : FR= 17 ; Archie exponent $m=1.90$

For the resistivity index, we have tried to use the theoretical calculation to derive resistivity at the entrance using the global resistivity. The results are not favorable. In fact, this method corresponds to a "two electrode" measurement with additional contact resistance due to the presence of oil covering the electrodes. It is well established that "four electrodes" are needed to ensure correct measurement (Sprunt et al., 1990; Fleury and Longeron, 1996) This is achieved by measuring the potential along the core. We used both the average saturation (sample 1) and the saturation calculated at the center of the core using a numerical simulator (sample 2). The resistivity index is then close to the results of standard methods with a saturation exponent close to 2 (Fig. 7).

4.4. Relative Permeabilities

The K_r determination using the analytical calculation and the overall pressure drop is not possible. The cause may be the same as for electrical measurements, i. e., an additional pressure drop at the contact between the end-piece and the sample. We also used the local pressure measurements.

For sample 2, the whole oil K_r curve is determined during drainage and only the end points during imbibition (Fig. 8). The results are very similar to direct measurements by the standard steady state method, using the same set-up (Fig. 8).

For sample 1 (Fig.9), the oil K_r is accurately determined, but for water there is only one value, since the negative P_c curve is vertical (water-wet sample). The low value for K_r (water) is also consistent with water wet samples.

5. Discussion

The capillary pressure curves were compared to centrifuge measurements with the same fluids (Fig. 6). The fit is good for sample #1, but the level of capillary pressure is too low for sample #2. For this high permeability sample (more than 1 darcy) the accuracy in pressure measurements is poor and may explain the difference (we used 10 bars pressure sensors). In addition, for both experiments, the saturation measurements are not very accurate for the following reasons:

- 1) some leaks in the fittings, especially at high pressure during negative imbibition,
- 2) dead volumes in pressure sensors, tubing and fittings,
- 2) leaks in the piston seals of the syringe pumps,
- 3) difficulty to measure the sample pore volume in the conditions of the experiment (effect of confining pressure, for instance).

We have studied the different causes of error and proposed improvements for subsequent measurements. For instance, we have designed an "in-situ" gas porosimeter to measure the pore volume.

We have shown that local electrical and pressure measurements along the sample are needed. There is no technical difficulty with these measurements, even at high pressure and temperature. For interpretation of the local measurements, we have shown that the average saturation was close to the local saturation in the center. However, a 1-D numerical simulation of the different steps in the displacement is needed for a better determination of local saturation, relative permeability and resistivity index.

6. Conclusion

This paper describes the first use of an Integrated Petrophysical Tool (IPT) on two reservoir rock samples.

The IPT is based on the steady-state injection of one fluid through the sample placed in a Hassler cell. The experiment leading to the whole Pc cycle consists of about 30 steps at various oil or water flow rates. It takes about four weeks to measure the following petrophysical properties:

- Complete capillary pressure cycle: primary drainage, spontaneous and forced imbibitions, secondary drainage
- End-points and parts of the relative permeability curves;
- Formation factor and resistivity index.

Relative permeabilities agree with steady-state measurements and capillary pressure with centrifuge measurements only for sample #1. There is no comparison for resistivity index, but the results are in agreement with literature data. For these experiments, special attention must be paid to the precise determination of effluent production. Above all, any fluid leakage must be avoided. In addition, an adjustment of the parameters using a 1-dimensional numerical simulator improves the accuracy of the measurements.

In conclusion, the Integrated Petrophysical Tool is as accurate as standard methods and has the advantage of providing the various parameters on the same sample and during a single

experiment. The IPT is easy to use and can be automated. In addition, it can be operated at reservoir condition.

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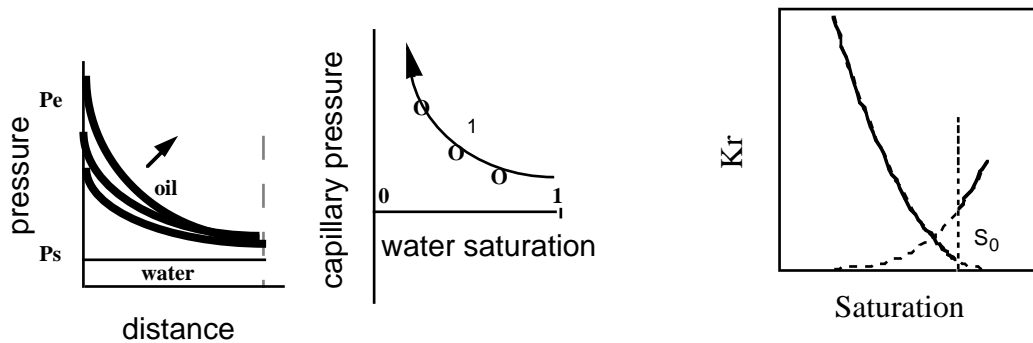


Fig. 1 - Pressure profiles and corresponding points on the P_c curves during an IPT measurement

Fig. 2 - Parts of the K_r curves determined during an IPT measurement.

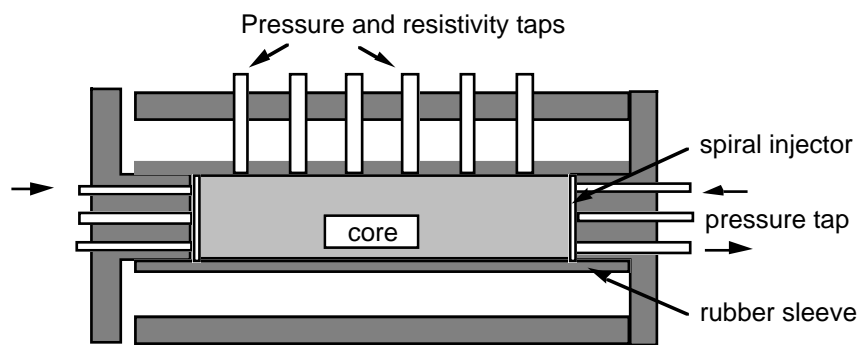


Fig 3 - Core-holder for the Integrated Petrophysical Tool.

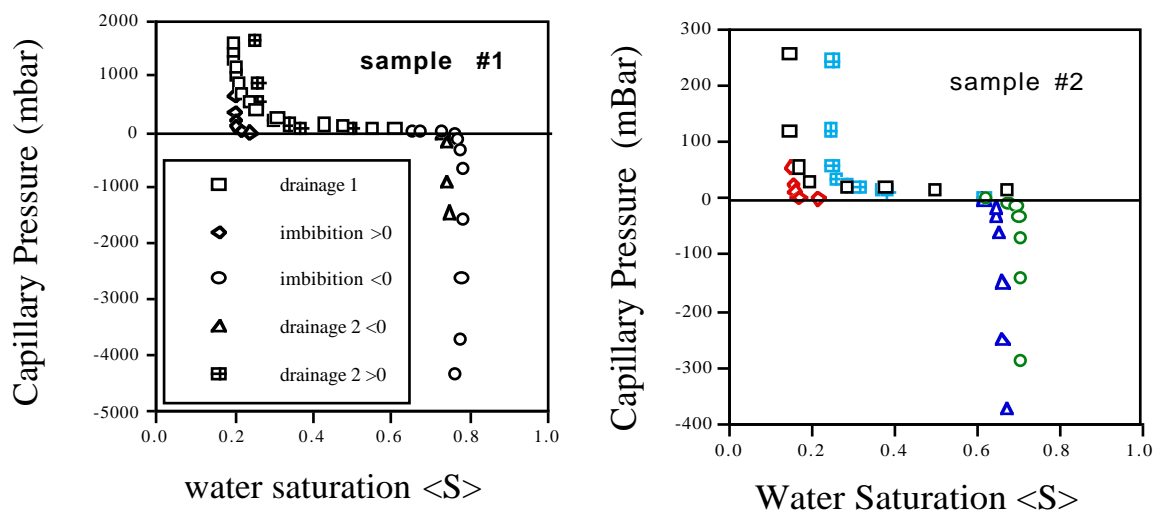


Fig. 4 - Capillary pressure cycles with average saturation.

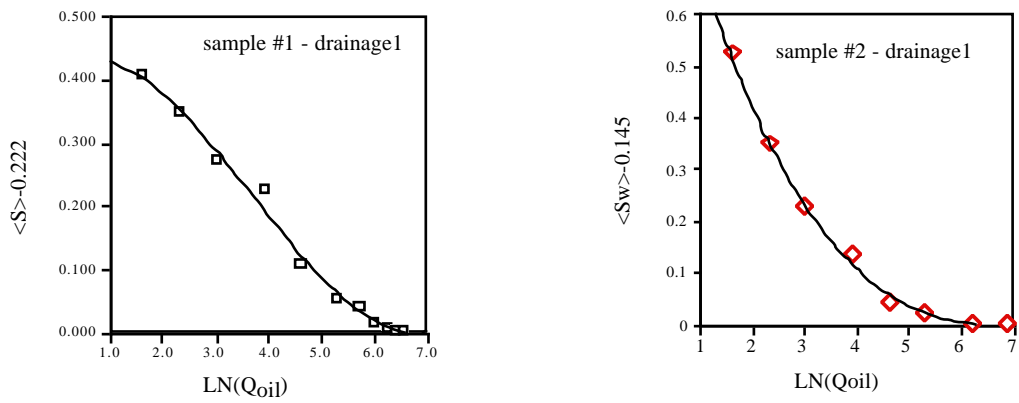


Fig. 5 - Calculation of the local saturation: approximation of $\langle S_w \rangle$ vs LN (Q) by a 3rd order polynomial

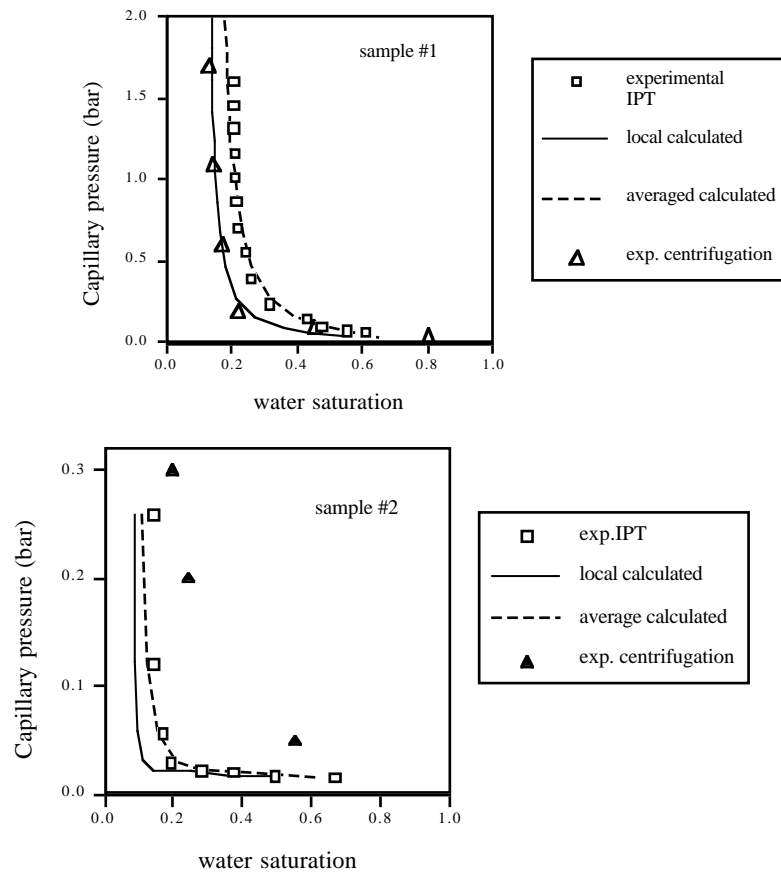


Fig. 6- Primary drainage P_c curves for sample #1 and #2: Average and local saturation and comparison with centrifuge data

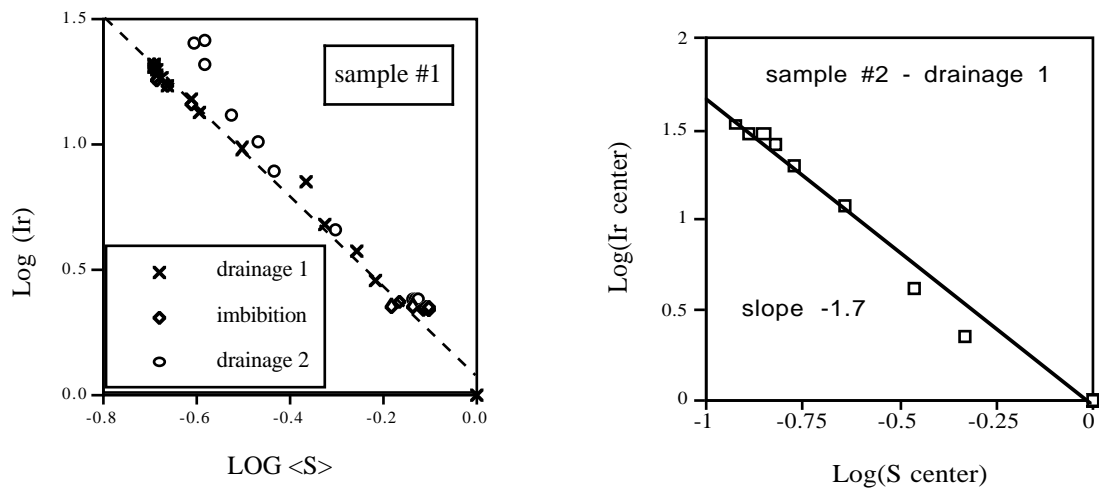


Fig. 7 - Resistivity index measurements

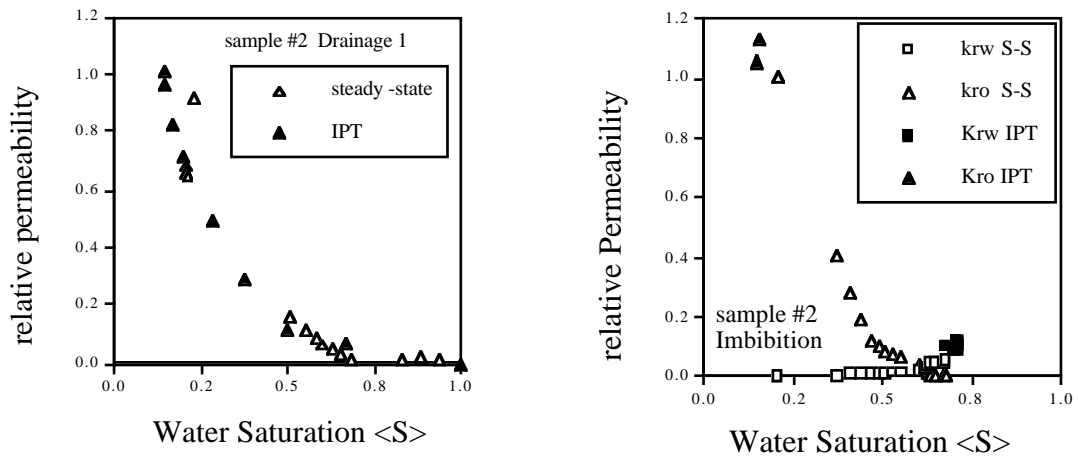


Fig. 8 Relative permeability. Comparison between steady-state (S-S) and IPT measurements.

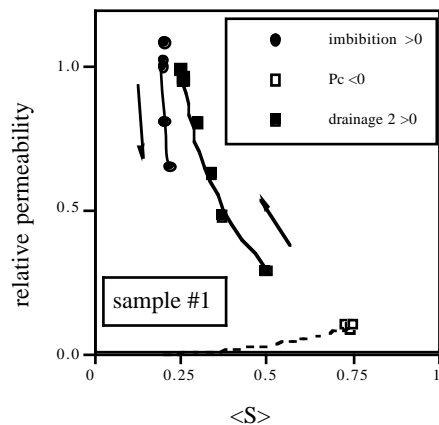


Fig. 9 - Relative permeability measurements for sample #1 (IPT)