A NEW APPROACH TO DERIVE RELATIVE PERMEABILITY DATA WHILE MEASURING RESISTIVITY INDEX

M. Fleury , P. Poulain, P. Egermann
Institut Français du Pétrole, Rueil-Malmaison, France

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Toronto, 21-25 August 2005

ABSTRACT

We describe a new approach to derive a set of relative permeability (Kr) curves while measuring the resistivity index using the FRIM method during imbibition at reservoir conditions. The methodology relies on (i) the accurate and continuous measurement of the average saturation of the sample (ii) the measurement of the "true" differential pressure across the sample excluding the effect of the ceramic (iii) the availability of a few equilibrium points in a multi-rate water injection experiment to deduce the capillary pressure curve. The Kr curves are deduced by history matching the pressure drop and saturation for each flow rate. Approximate analytical curves can also be found using a method similar to the analytical interpretation of Semi Dynamic Method data. Although the sample is short, the resistivity derived saturation is very accurate and allows a very good estimation of its time derivative as well as the extrapolation at infinite time of the equilibrium saturation at each flow rate.

The proposed procedure, although less precise than more sophisticated Kr measurements involving local saturation measurements, does not necessitate any additional time and is therefore extremely useful to compare or integrate various information in a SCAL program. The results obtained on homogeneous oil wet carbonate samples show that relevant Kr curves can be derived using this process since they are comparable to data obtained through conventional technique (unsteady state experiment on long core).

INTRODUCTION

Resistivity index (RI) and relative permeability (Kr) data collection are usually separate SCAL programs with very different objectives. RI data usually collected in conjunction with capillary pressure, are used to estimate original oil in place, while Kr data are dedicated to the prediction of the dynamic behavior of a reservoir and the estimation of reserves. These data are also used by different groups, respectively well log analysts and reservoir engineers.

The objective of this paper is to demonstrate that relative permeability curves can be extracted in the context of the FRIM method, allowing a simultaneous estimation of

electrical and flow properties for oil in place and reserves estimation. Essentially, the method can be very helpful to prove the coherency between different experiments performed on different samples in a SCAL program.

We describe first the experimental set-up used for collecting the data. It is mainly the same as the one used for performing resistivity index measurements in drainage and imbibition at reservoir conditions with a small modification related to the measurement of the pressure drop. Then, the interpretation methodology is described, relying heavily on previous work related to multi-rate water flooding experiments. Finally, an example is given and the limitations of the method discussed.

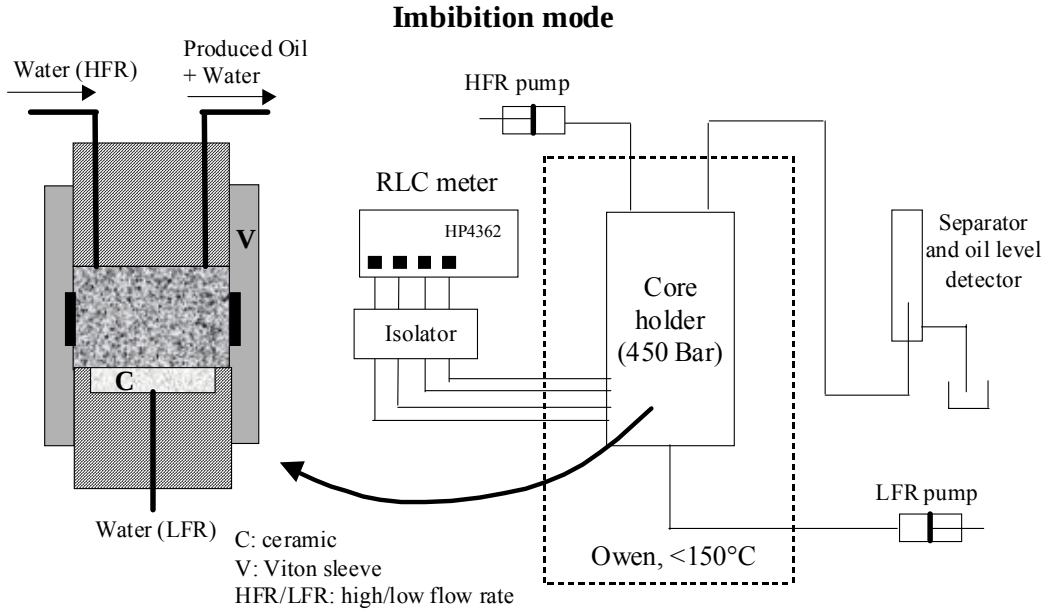


Figure 1: Experimental set-up in imbibition. Water is injected at a variable low flow rate (LFR) through the ceramic. At the outlet face, a spiral allows the produced oil to be collected and measured quickly outside the oven without significant delay compared to the resistance (HFR circuit).

EXPERIMENTAL SET-UP

We describe in this section how we collect the data necessary for the calculation of relative permeability curves: average saturation and pressure drop versus time. The experimental set-up used was initially designed to collect resistivity index data during imbibition (Fleury, 2003, Figure 1) at reservoir conditions in the framework of the Fast Resistivity Index Measurements (FRIM) method. The cell is designed for short samples (length 3 cm, diameter 4 or 5 cm), an advantage when considering experimental duration, a disadvantage when considering saturation measurement errors. The radial electrode geometry is a key element of the device and allows a measurement of the average resistance of the entire sample, later converted into an average saturation (see below). To

derive Kr curves, we added the measurement of the pressure drop across the sample excluding the ceramic, as explained below.

The drainage and spontaneous imbibition cycles performed on the sample prior to forced imbibition is not described in this paper and can be found elsewhere (Fleury, 2003, Fleury *et al.* 2004). Assuming a homogeneous sample, the saturation profile obtained at the end of the drainage-spontaneous imbibition cycles is uniform because a ceramic is present at one face (Figure 1). This uniform profile is obtained if stability is reached at the last capillary pressure step.

Measurement of the pressure drop

The total pressure drop (sample + ceramic) can obviously easily be measured as in any flooding experiment. However, this information is not very useful because the pressure drop generated by the ceramic is dominant. Moreover, the removal of the ceramic contribution would require an unrealistic accuracy and stability of the ceramic permeability, as shown by Lenormand *et al.* (1995). Using composite ceramics or membranes with low pressure drop and high entry pressure does not solve the problem. Removing the ceramic to perform imbibition could be an alternative but it is not very practical because of the perturbations generated by the temperature decrease and the stress release when dismounting the cell.

To circumvent all these difficulties, we included in the end-piece supporting the ceramic four pressure taps to allow the measurement of the average pressure drop of the sample without the influence of the ceramic. In general, a pressure tap contacting the face of a sample allows measuring the highest pressure at the location of the hole. Therefore, when injecting water at a higher pressure than oil during forced imbibition, we are able to measure the water pressure drop across the sample only.

Measurement of the average saturation using resistance

The measurement of resistance is very precise since standard apparatus can provide easily a relative accuracy of 0.1%. In addition, the resistance considered at reservoir conditions lies in the middle range of measurement (1-1000 Ohm). Therefore, a resistivity-derived saturation will be much more precise than saturation measured directly at the separator by volumetric balance. Due to the short samples used and corresponding small pore volumes (10 to 20 cc), the situation is also not very favorable.

The resistance is measured using a radial electrode geometry. When a saturation profile S(z) is present in the sample, it has been shown (Fleury, 1998) that the measured resistance R corresponds to a parallel summation of resistance:

$$R = \frac{1}{L}\int_0^L \frac{1}{R(z)}\,dz \qquad (1)$$

where R(z) is the resistance corresponding to S(z). For this reason, the measured resistance is weakly sensitive to the saturation profile and allows deducing the average saturation with a reasonable accuracy. This assumption can be checked during the interpretation process and will be presented later.

The relationship between resistance and saturation is sometimes complex and a simple Archie law can be insufficient. We propose to use a more general formulation that includes the Archie formulation:

$$\frac{R}{R_0} = RI = Sw^{-n1}\frac{1+C}{1+CSw^{-n2}} \quad (2)$$

where R_0 is the resistance of the sample at 100% saturation. In general, n_1, n_2 and C can be fitted using the measured saturation Sw from the separator, and the measured resistance, as in Fleury (2003) and Fleury *et al.* (2004). Then, the relationship 2 must be inverted to deduce the saturation Sw as a function of R using any appropriate mathematical method (e.g. a polynomial form in log-log scale as in Fleury, 2003). The resistance being recorded continuously, we obtain an accurate measure of Sw versus time for the entire experiment.

METHODOLOGY

We describe in this section the methodology used to perform the experiment and interpret the collected data, pressure drop and average saturation versus time, in terms of relative permeability and capillary pressure.

General approach

The most appropriate procedure is to perform a multi-rate experiment in order to deduce the capillary pressure curve. Then different levels of interpretation can be performed, either based on analytical or numerical approaches (Figure 2). This approach is essentially the same as the one proposed by Egermann and Lenormand (2004), except that the heterogeneity issues at the centimeter scales cannot be tackled because no local saturation measurement is performed. Sample homogeneity is assumed, a reasonable assumption given the small sample size.

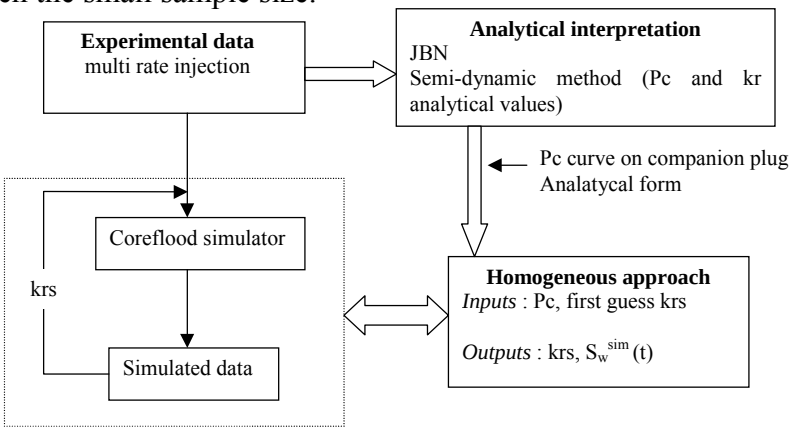


Figure 2: Schematic of the data interpretation workflow.

Analytical approach

As a first step, an analytical interpretation can be performed using the techniques used for the Semi-Dynamic Method (Ramakrishnan and Capiello, 1991; Lenormand et al., 1995, Lombard *et al.*, 2002). In a multirate experiment, the stabilized saturation data and pressure drop can be used to deduce a few points of the capillary pressure curve and the relative permeability curve of the injected phase (water in the case of forced imbibition):

$$S_{inlet}(\Delta P_i) = \bar{S} + q\frac{d\bar{S}}{dq} \tag{3}$$

$$kr^{inj} = \frac{\mu L}{KA}\frac{dq}{d\Delta P_i} \tag{4}$$

where q is the flow rate, $\bar{S}$ the average saturation deduced from the measured resistance, ΔP_i is the stabilized pressure drop. Note that the derivative of saturation vs. flow rate is needed, and hence, the choice of an appropriate flow rate sequence is required. Our experience indicates that very low flow rates are necessary (around 0.1 cc/hr) to obtain data points in the intermediate saturation range. In this context, a short sample (a small pore volume) is an advantage because an equilibrium saturation and pressure drop can be obtained within a reasonable experimental time (a few days) at this very low flow rate. If needed, an extrapolation procedure can also be applied to extract the saturation at infinite time.

Numerical approach

The analytical solution calculated above can be used as "first guess" input for the history matching loop involving the numerical simulation of the experiment (Figure 2). Note that a standard simulator can be used without the need for including a ceramic effect, often difficult to implement in terms of boundary conditions. At this step, a model of capillary pressure and relative permeability curve is necessary to perform the simulation.

EXAMPLE

We illustrate the different steps described above using an experiment performed on a low permeability carbonate sample (see Table 1 for the main characteristics) at pseudo-reservoir conditions (dead oil, reservoir temperature, confining stress). NMR and mercury injection indicate a unimodal pore size distribution.

Table 1: Sample and fluid characteristics

Length (cm)	3.12
Diametre (cm)	3.98
Porosity	0.206
Pore volume (cm^3)	8.1
Swi	0.46
Water Permeability (mD)	0.13
Crude oil viscosity @ 101 °C (cP)	1.8
Brine viscosity @ 101 °C (cP)	0.45

The first drainage cycle yielded an irreducible water saturation of 0.46 (at Pc max=4 bar). No production was observed during spontaneous imbibition when reducing gradually Pc down to zero. This behavior is consistent with wettability tests performed on other samples of the same formation that indicated wettability indices around -0.8. The forced imbibition was performed after completed stabilization of the zero Pc step using three flow rates (0.1, 0.2 and 1 cc/hr).

Step 1: production and pressure drop curves

The relationship between resistivity and saturation is first evaluated using the oil production measurement at the separator (Figure 3). We show the four data points corresponding to the four equilibrium states with no saturation variations (the initial state after spontaneous imbibition and the end of the three flow rates). In the present case, the saturation can be calculated using a simple Archie relationship:

$$R = 33.74\, Sw^{-2.33} \qquad \Leftrightarrow \qquad Sw = \left(\frac{33.74}{R}\right)^{1/2.33} \tag{5}$$

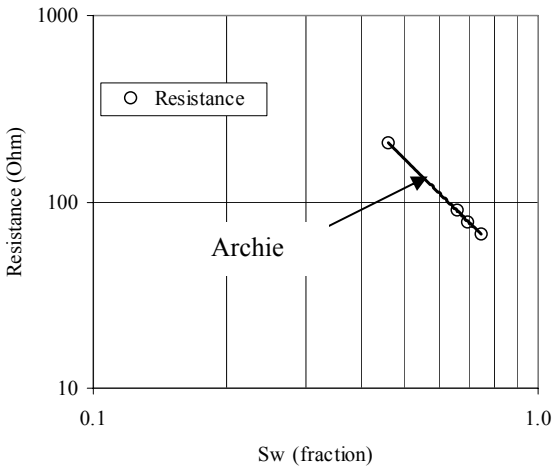


Figure 3: Resistance versus the saturation measured at the separator at the end of each flow rate. An Archie law is adequate for describing the data (straight line).

The above relationship is then used to calculate the average saturation vs. time from the measured resistance (Figure 4, the oil production instead of water saturation has been plotted). Clearly, it would not be possible to determine such a production curve from standard separator measurements due to the very small volumes involved. Note that the total duration of the experiment is about 80 hrs, despite the use of very small flow rates. When the flow rate is switched to a larger value, a peak on the pressure drop curve is observed as expected. The small fluctuations during the first flow rate (*e.g.* t=18 hr) are due to small temperature fluctuations.

Step 2: analytical interpretation

From the analytical expression (Eq. 3 and 4), we can calculate three points of the capillary pressure curve (Figure 5). The equilibrium saturation reached at the end of the

lowest flow rate is already relatively high (0.73) because the sample has a small permeability. Therefore, capillary forces can be balanced by viscous forces very easily. This would not be the case for higher permeability sample and similar wettability states. In the present situation, obtaining a point in the plateau region of the Pc curve (around 0.6) would require a flow rate much smaller than 0.1 cc/hr. This is technically possible but requires a very precise temperature regulation. We show also on Figure 5 the capillary pressure curve used later during the history matching procedure. The shape of the curve is clearly consistent with an oil wet state.

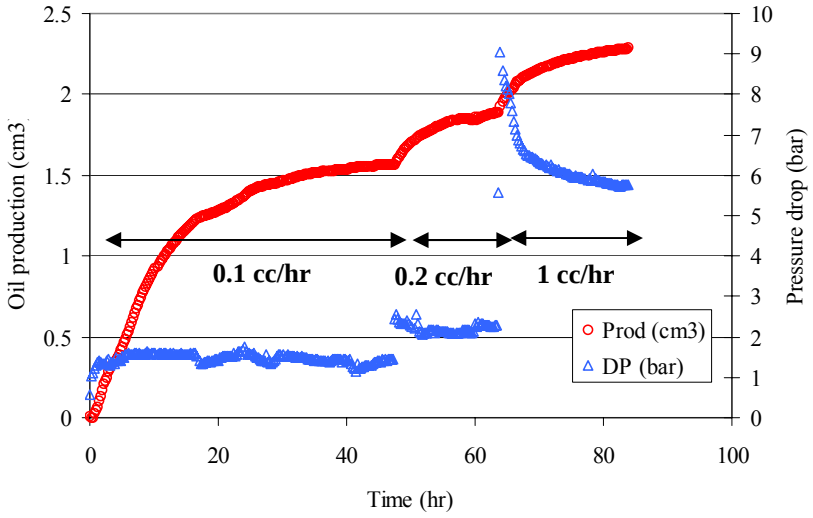


Figure 4: Production curve deduced from the recorded resistance and pressure drop.

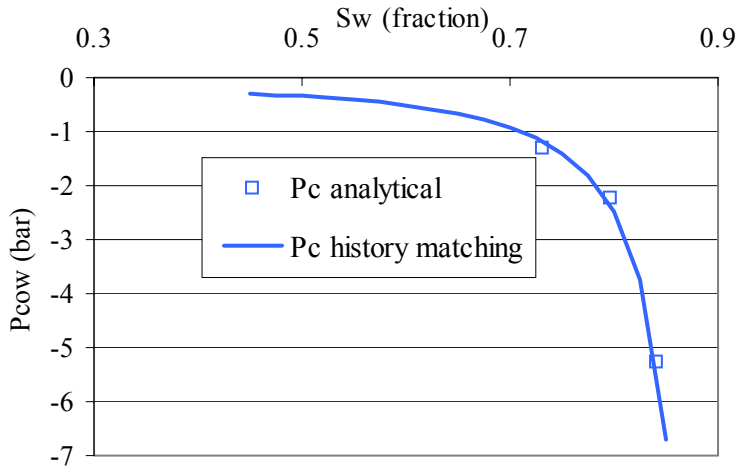


Figure 5: Capillary pressure points deduced from the analytical expression (Eq. 3) and Pc curve calculated during the history matching procedure.

Similarly, three points of the water relative permeability curve can be obtained directly from the data (Figure 6). We fitted the experimental points with an exponential function

in order to extract the derivative of flow rate vs. pressure drop, as performed also by Lenormand *et al.* (1995) or Lombard *et al.* (2002).

Step 3: numerical interpretation

The history matching procedure takes advantage of all the available transient data and therefore provides the final desired information. For the Pc curve, we used a Brooks-Corey type power law of the following form to extrapolate/interpolate in the entire saturation range (Brooks and Corey, 1966):

$$P_c^{ana}(S_w) = P_c^{threshold}\left(\frac{1-S_{wi}-S_{orw}}{1-S_w-S_{orw}}\right)^{\lambda} \qquad (6)$$

The coefficients are adjusted so as to fit the analytical points. Using this Pc curve, the relative permeability curves are history matched so as to fit the production and pressure drop curves (Figure 7). The resulting set of Kr curves is shown on Figure 8a. It is worth pointing out that the relative permeability curve of the injected phase derived from the history matching procedure is in very good agreement with the analytical values obtained from the stabilized states at the end of each injection sequence.

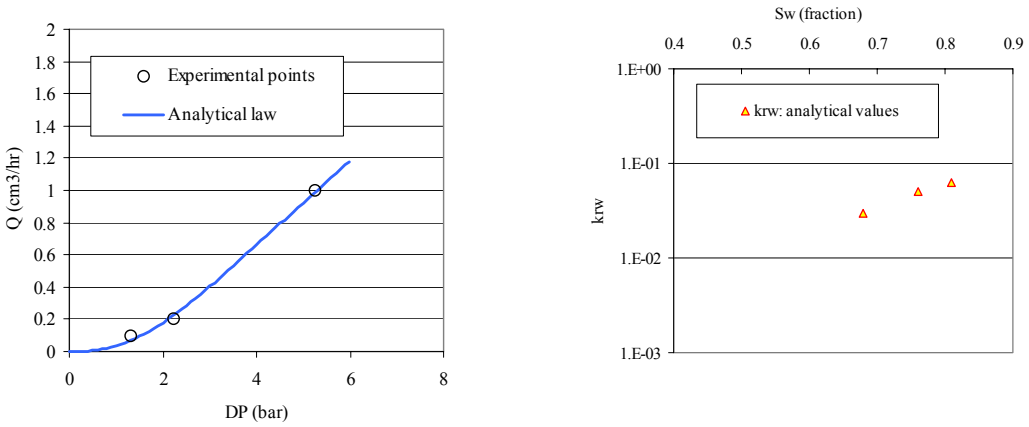


Figure 6: Calculation of the analytical Kr points (right) from the experimental Q(ΔP) points (left) using Eq. 4. For the latter, the data have been fitted using an exponential function in order to calculate the derivative.

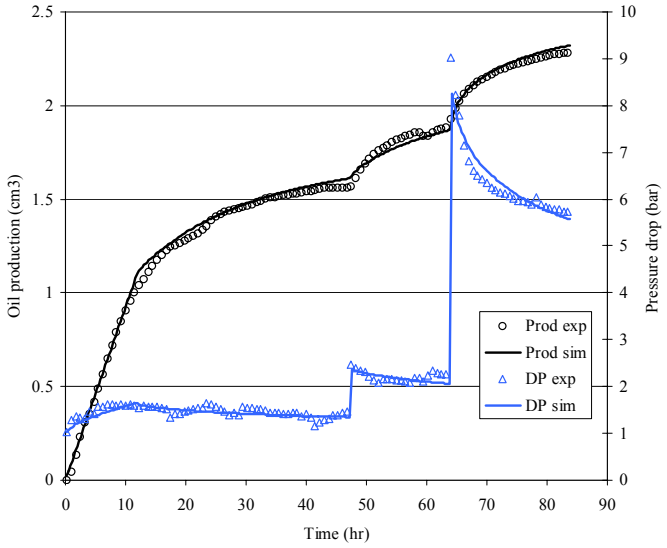


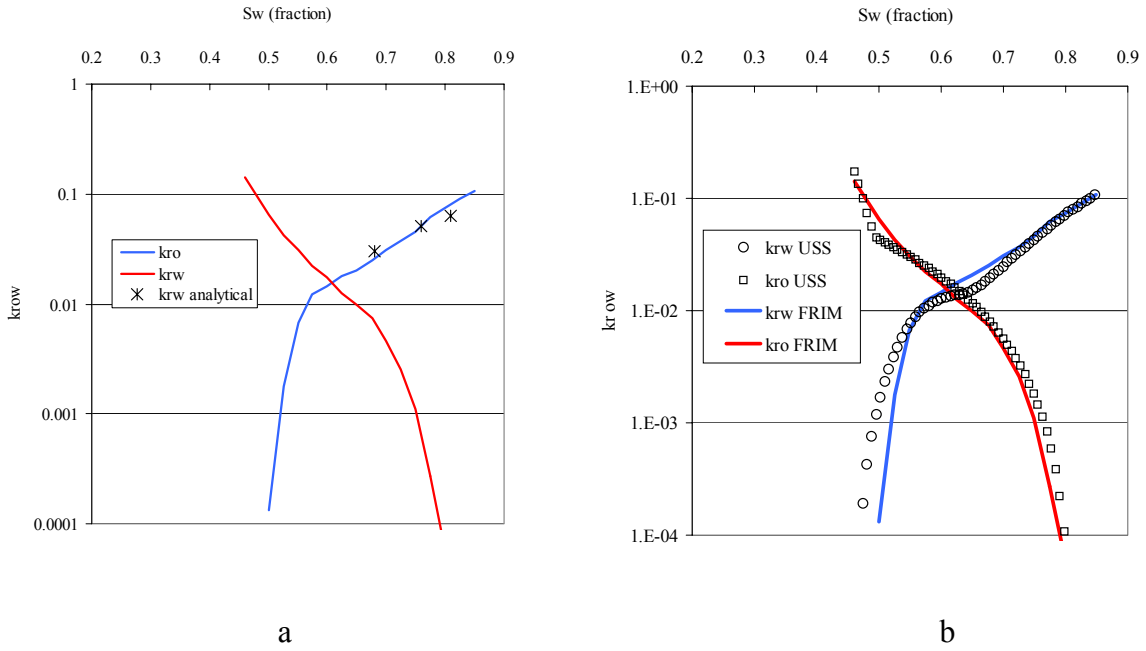
Figure 7: History matching of the production curve deduced from the measured resistance and the pressure drop.

DISCUSSION

Comparison with unsteady state Krs curves

In this section, we compare the Krs curves obtained using the above described approach with the set of curves obtained using a conventional USS technique, routinely applied in the oil industry. A companion plug (5 cm in diameter and 7 cm in length) cored in a neighboring location and aged in the same conditions was used to collect these "reference" data. The sample was mounted in a confining pressure Hassler core holder and the waterflood was conducted in the same thermodynamic conditions as the resistivity experiments. The USS Krs curves were deduced by history matching the production data (pressure drop and recovery) with full account of the capillary pressure for the end effects (Honarpour *et al.*, 1986).

Figure 8b demonstrates that very similar curves were obtained with the two approaches confirming that interesting features related to the flowing properties of the rock can be deduced during a resistivity experiment using the FRIM procedure. The comparison also evidences that the cross-over point of the Krs curves, in particularly, are very consistent, which is very interesting and relevant information to anticipate the performance of the waterflood. Therefore, these additional information collected during the resistivity experiments can contribute significantly to gain confidence in the data introduced in the simulators to predict reservoir performance.



a b

Figure 8: (a) oil and water relative permeability curves deduced from history matching with the analytical points calculated at step 2 for comparison – (b) comparison between the Krs curves obtained with FRIM and those obtained on a companion plug using the conventional USS technique.

Accuracy of the proposed approach

The accuracy of the method strongly relies on the appropriate sequence of flooding rates for obtaining capillary pressure data. This sequence must be chosen such that the equilibrium saturation covers the entire saturation range, especially close to the initial saturation. For example for the case considered here, the relative permeability curves will be the most accurate in the saturation range [0.6 - 0.85] where equilibrium points are available. For Sw<0.6, the choice of the capillary pressure curve model is critical and can influence the resulting Kr curves, as usual.

Effect of saturation profile on resistivity

A key assumption is that the resistance measured using a radial electrode geometry provides an accurate estimate of the average saturation, unbiased by the saturation profiles. Unlike a standard longitudinal face-to-face electrical measurement, a radial electrode geometry can compensate for relatively sharp saturation profiles because this geometry provides a parallel summation of resistance (this is the basic idea of the FRIM method but the shape of the saturation profiles during drainage is different). Using the Pc-Kr curve set found during the history matching, we calculated the profiles at the end of each flooding rate (Figure 9). Then, we can calculate the following average saturation Sw:

$$Sw = \frac{1}{L}\int_0^L \frac{1}{S(z)}dz \qquad (7)$$

corresponding to the average performed by the electrical measurement (Eq. 1). It can be seen that the average saturation deduced from the resistance using Eq. 5 is very close to the average calculated from Eq. 7 above (Table 2). Therefore, this assumption is fully justified.

Table 2: Comparison of resistivity derived average saturation and the average saturation deduced from the simulation using a parallel resistance model.

	<Sw> exp	<Sw> sim	Erreur
End of 0.1 cc/hr	0.66	0.658	-0.2 %
End of 0.2 cc/hr	0.695	0.69	-0.5 %
End of 1 cc/hr	0.744	0.748	0.4 %

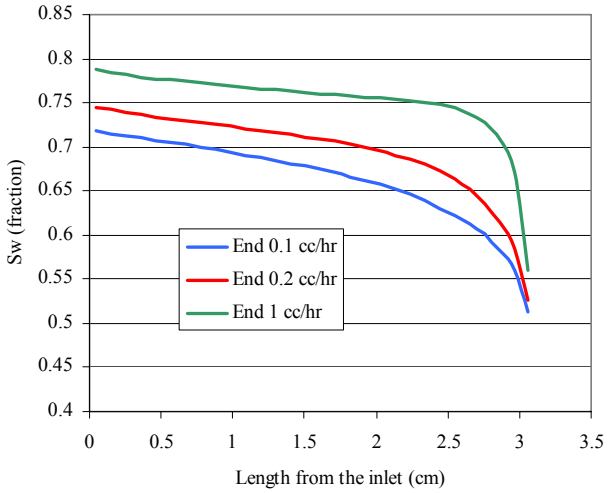


Figure 9: Saturation profiles calculated at the end of each flow rate before switching to a new value.

CONCLUSION

Using a multi-rate water flooding sequence performed after drainage and spontaneous imbibition in a "porous plate type" experiment, we show that relative permeability curves can be calculated with a reasonable accuracy. The data used are the average saturation calculated from the average resistance of the sample, and the pressure drop for each flow rate. The proposed method is applicable if a radial electrode geometry is used and the pressure drop is not influenced by the ceramic.

The proposed method can contribute significantly to prove the coherency between different experiments performed on different samples in a SCAL program and to gain confidence in the data introduced in the simulators to predict reservoir performance.

ACKNOWLEDGMENTS

The authors want to thank IFP for permission to publish these results.

REFERENCES

Brooks R. H. et Corey A. T. : "Properties of porous media affecting fluid flow", J. Irrig. Drain. Div.,vol 2, pp 61-88, 1966.

Egermann P. and Lenormand R., "A new methodology to evaluate the impact of the local heterogeneity on petrophysical parameters (kr, Pc) : application on carbonate rocks", SCA n° 2004-18, Society of Core Analysts, Abu Dhabi, 2004.

Fleury M., 'FRIM: a Fast Resistivity Index Measurement Method', Proceedings of the International Symposium of the Society of Core Analysts, The Hague, September 14-16, 1998.

Fleury M., "Resistivity in carbonates: new insights", Proceeding of the International Symposium of the Society of Core Analysts, Monterey, 22-25 September 2002.

Fleury M., 'Advances in Resistivity Measurements using the FRIM Method at Reservoir Conditions. Applications to Carbonates.' Proceedings of the International Symposium of the Society of Core Analysts, September 2003, Pau, FRANCE.

Fleury M., M. Efnik, M.Z. Kalam, "Evaluation of water saturation from resistivity in a carbonate field. From laboratory to logs". Proceedings of International Symposium of the Society of Core Analysts, Abu Dhabi, UAE, 5-9 October 2004.

Honarpour M, Koederitz L, and Harvey A.H. : "Relative permeability of petroleum reservoirs", CRC Press, 1986.

Lenormand R., Eisenzimmer A., and Delaplace P., "Improvements of the Semi-Dynamic Method for Capillary Pressure Measurements", SCA n° 9531, Society of Core Analysts, San Francisco, California, 1995.

Lenormand R., P. Delaplace, P. Schmitz, "Can we really measure the relative permeabilities using the micropore membrane method", Proceeding of the International Symposium of the Society of Core Analysts, Montpellier. 1996

Lombard J.-M., Egermann P., and Lenormand R., "Measurement of Capillary Pressure Curves at Reservoir Conditions", SCA n° 2002-09, Society of Core Analysts, Monterey, California, 2002.

Ramakrishnan, T. S. and Capiello, A.: "A new technique to measure static and dynamic properties of a partially saturated porous medium," Chem. Eng. Sci., (1991) pp 1157-1163.