Interrelationship between resistivity and relative permeability of a carbonate rock during drainage and imbibition experiments

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ABSTRACT

Capillary pressure and relative permeability are the key parameters for understanding fluid flow in porous media, and more specifically for estimating oil reserves and planning a production scenario. They are determined in the laboratory using special core analysis (SCAL) techniques. Since they are both functions of fluid saturation, correlations between them and resistivity may exist. In this paper we report a way of deriving relative permeability from resistivity measurements based on Li's approach [6] during a steady-state flow experiment for both primary drainage and imbibition cycles performed on a carbonate outcrop.

Li's starting assumption is that the brine relative permeability is inversely proportional to the Archie resistivity index RI [1]. Li then derived a relationship between brine relative permeability and resistivity index RI during a primary drainage cycle. A comparison between relative permeability inferred from resistivity and that derived from capillary pressure experiments gave acceptable agreement. To validate the model, Pairoys et al. [9] studied the effect of different flow displacements on the resistivity response during a primary drainage. The key results were that the steady-state flow experiment provided reliable correlation between Kr and resistivity and thus a new way to estimate Kr.

Since imbibition process is more representative of a waterflooding in a reservoir, an extension of Li's model is proposed for the steady-state imbibition cycle. Using the proposed imbibition model, a good match between the experimental steady-state Kr and Kr derived from the resistivity model was obtained. Additional investigations such as effects of wettability and rock heterogeneities on these results will be necessary to validate the generality of the overall workflow. If validated, it would provide an in situ measure of relative permeability, for example as a continuous log or from a permanent resistivity sensor.

INTRODUCTION

Both relative permeability Kr and capillary pressure Pc are the key petrophysical parameters governing fluids flow in porous media. They are dependent also on reservoir rocks and are usually determined in the laboratory using conventional and special core analysis. If an analogy between fluid flow and electrical flow really exists, resistivity, capillary pressure and relative permeability should correlate.

Several theoretical models have been proposed in the past to infer relative permeability from capillary pressure (Purcell [11], Burdine [3], Corey [4], Brooks-Corey [2]). But only a few studies were initiated to correlate relative permeability and/or capillary pressure with resistivity. Pirson et al. [10] found an empirical relationship between relative permeability and resistivity index. Li et al. [6], [7] developed a semi-analytical model to infer relative permeability from resistivity and confirmed it using experimental data. Both resistivity and relative permeability were measured simultaneously in the laboratory. Encouraging agreement was found between Kr from core flooding experiments and Kr inferred from resistivity logs. Pairoys et al. [9] studied the effect of fluid displacement processes with resistivity measured during unsteady and steady-state flow and resistivity measured at capillary equilibrium (using the porous plate method). A key finding was that the steady-state experiment should be preferred.

In the present study, Li's approach [7] is used as the starting point for inferring wetting-phase relative permeability from resistivity data during the primary drainage. The Purcell [11] and Brooks-Corey [2] approaches are then used to calculate both wetting and non-wetting phase relative permeabilities. An extension of Li's model is proposed for the imbibition cycle and a good agreement between the experimental steady-state Kr and Kr derived from resistivity measurements in imbibition is shown.

This work was motivated by the fact that there is no reliable technique to measure downhole relative permeability. If a valid correlation can be found, an in situ relative permeability at the reservoir scale using logging techniques could be imagined, either as a continuous log or based on permanent downhole resistivity sensors.

BACKGROUND

The guiding principle here is the analogy between fluid flow in a porous medium and electrical flow in a conductive body. The wetting phase relative permeability is assumed to be inversely proportional to the Archie resistivity index RI [1]. Li et al. [6] then derived a relationship between relative permeability of the wetting phase and resistivity index RI during a primary drainage cycle:

$$\mathrm{Krw} = \mathrm{Sw}^{*}.\frac{1}{\mathrm{RI}} \ \text{ with } \ \mathrm{Sw}^{*} = \frac{\mathrm{Sw} - \mathrm{Swi}}{1 - \mathrm{Swi}} \qquad \text{Eq. 1}$$

Where Krw is the wetting phase relative permeability, RI is the resistivity index, and Sw* is the normalized or effective saturation of the wetting phase in primary drainage.

Also, according to Li and Horne [5], the wetting phase relative permeability can be calculated using the Purcell approach [11] and the non-wetting phase calculated using the Brooks-Corey model [2]:

$$\mathrm{Krw} = \mathrm{S}_{\mathrm{w}}^{*\ (2+\lambda)/\lambda} \qquad \text{Eq. 2}$$

$$\mathrm{Kro} = (1 - \mathrm{S}_{\mathrm{w}}^{*})^{2}(1 - (\mathrm{S}_{\mathrm{w}}^{*})^{(2+\lambda)/\lambda}) \qquad \text{Eq. 3}$$

Where λ is the pore size distribution index and is fit to the capillary pressure curve. In the absence of Pc curve, the value of λ is determined by tuning its value to match the Krw curve obtained from Equation 1. This value is then subtituted in Equation 3 to obtain the non-wetting phase relative permeability Kro.

On the normalized scale, the model for primary drainage is constrained by boundary conditions which are well known for the wetting phase: at Sw*=1, Krw=RI=1 and at Sw*=0, Krw=0.

For the imbibition cycle, the same model can be used (Equations 2 and 3), except that a normalization of the RI data points is required:

$$\mathrm{Krw} = \frac{\mathrm{Sw}^{*}}{\mathrm{RI}^{*}} \ \text{with } \ \mathrm{RI}^{*} = \frac{\mathrm{RI}}{\mathrm{RI}_{\min}} \ \text{ and } \ \mathrm{Sw}^{*} = \frac{\mathrm{Sw} - \mathrm{Swi}}{1 - \mathrm{Swi} - \mathrm{Sor}} \qquad \text{Eq. 4}$$

With RI* the normalized or effective resistivity index and $\mathrm{RI}_{\min}$ the minimum resistivity index obtained at residual oil saturation Sor. The boundary conditions are: at Sw*=0, Krw=0, Kro=1, and at Sw*=1, Kro=0, RI*=1.

To “un-normalize” the Kr curves, end-point relative permeabilities Kro(Swi) and Krw(Sor) have to be determined from coreflooding experiments at the end of the primary drainage and imbibition cycles. Kr in drainage is obtained by dividing the effective permeabilities by the absolute permeability, whereas Kr in imbibition is obtained by dividing the effective permeabilities by the relative permeability to oil at irreducible water saturation Kro(Swi).

POROUS MATERIAL AND FLUIDS

A vuggy grainstone outcrop block was used for this study. The rock was a very porous ooid non-skeletal grainstone with mouldic pores. The porosity was enhanced by dissolution. Grains are well rounded and sorted. No fractures or clay are present.

Three rock slab models obtained from a same carbonate rock block, as detailed in the paper from Pairoys et al. [8], were prepared for the study. After a conventional cleaning (Soxhlet extraction), the core samples were saturated with 200 kppm NaCl brine. The porosity by weight and absolute permeability to brine were then measured (Table 1):

	Rock slab prepared for:	Porosity by weight ϕ (%)	Pore volume (cc)	Brine permeability (mD)
L1	Pc RI test	40.40	23.2	1800
L2	SS flow	38.33	22.2	1311
L3	USS flow	39.88	23.1	1737

Table 1: Properties of the three rock slabs

For the two-phase flow experiments, paraffinic oil (Soltrol 130) was used as non-conductive and non polar oil phase. Fluid properties are listed in Table 2:

	Density (g/cc)	Viscosity (cp)	Resistivity (Ω.m)
Brine	1.14	1.55	0.047
Soltrol 130	0.75	1.60	X

Table 2: Fluid properties

The contrast of viscosity was chosen to be small in order to limit viscous fingering during two-phase flow; stable displacements are expected since the mobility ratios were less than 1 in both primary drainage and imbibition.

A rock slab flooding setup was used to run the three experiments of (1) capillary pressure Pc, (2) steady-state relative permeability Kr_{SS}, and (3) unsteady-state relative permeability Kr_{USS} experiments. Resistivity was measured using 4-contact electrodes configuration as described by Pairoys et al. [8]. The distance between the two potential electrodes was 2.54 cm. Frequency of 1 KHz was used and all flooding tests were run at ambient pressure and temperature.

Because the unsteady-state technique gave a too high value of apparent saturation exponent n for such water-wet carbonate rock (L3), data results during the primary drainage are not detailed in the paper; resistivity has to be measured at equilibrium and not at a transient condition.

TWO-PHASE FLOW RESULTS

Drainage Pc-RI Experiment on L1:

Pc-RI experiment was performed to validate the saturation exponent value n determined from the steady-state experiment. Figure 1 represents the resistivity index RI curve, the capillary pressure Pc curve, and Kr inferred form Pc using both Li and Brooks-Corey models:

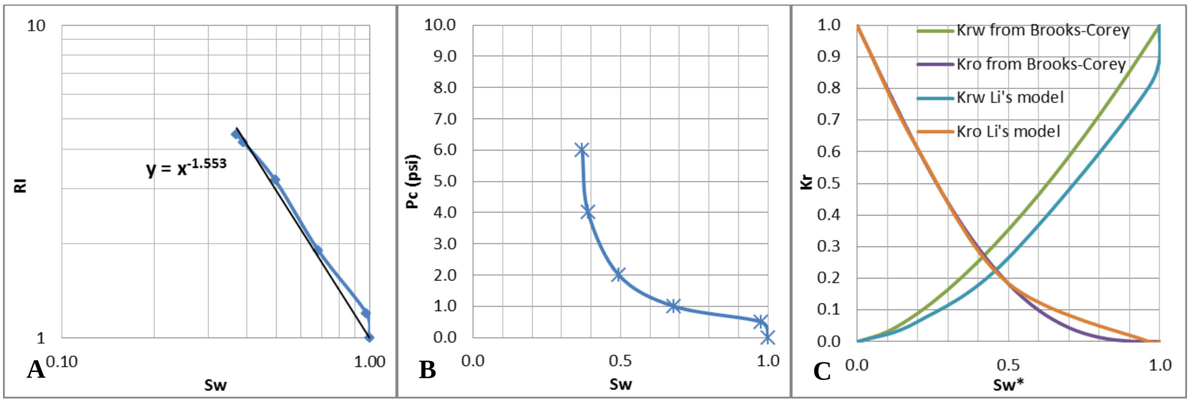

Figure 1: Data results from the drainage Pc-RI test on L1

A saturation exponent n equal to 1.55 was obtained from the Archie linear regression of the resistivity index curve. Normalized drainage relative permeability curve derived from capillary pressure could be estimated using the Brooks-Corey model. But un-normalized curve cannot be directly determined without a measure of Kro(Swi) at the end of the test.

Drainage Kr SS Experiment on L2:

The validation of the model detailed in the background section can be obtained by running a flooding experiment with direct measurements of Kr. The steady-state experiment was performed on the limestone L2. The relative permeability of each phase is calculated from the generalized Darcy's law. The base permeability to determine the relative permeability in drainage is the absolute permeability in (Table 1). The measurements were performed at six different ratios Q_w, Q_o with a constant and total flow rate Q_t equal to 1 cc/min.

Resistivity measurements were recorded at the end of each step when the brine production ceased and when the resistivity was stable. The resistivity index RI along with λ and Equation 1 were used to determine Krw. This was done by matching the Krw calculated from Equation 2 and the Krw directly obtained from the resistivity measurements (Equation 1). It is important to note that Sw has to be first normalized. The best fit between Krw from Equation 1 and Krw from Equation 2 is obtained for λ=3.75 (Figure 2):

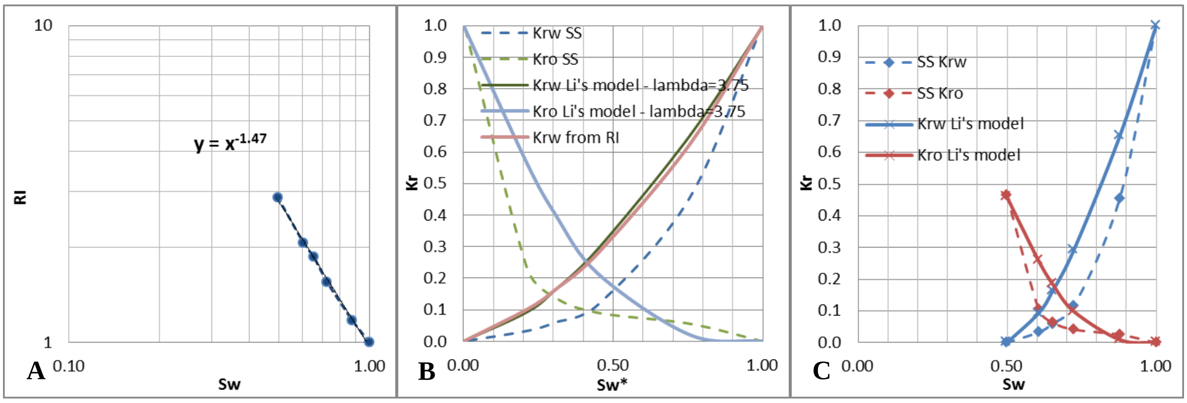

Figure 2: Data results from the drainage Kr SS test on L2

The irreducible water saturation S_{wi} at the end of the SS experiment was high due to the low differential pressure ΔP during the flow and above all due to capillary end effects. Other factors such as channeling could also explain the high Swi value.

-Graph A, Figure 2: the drainage Archie saturation exponents n was found equal to 1.47, which is close to the value obtained from the reliable Pc-RI test (n=1.55); this confirms the preference of the steady-state method to get both resistivity index and relative permeability curves. For the unsteady-state test, n was equal to an unreasonable high 3.25 for these well-defined water-wet core samples. The advantage of the steady-state method is that the resistivity data were taken at equilibrium.

-Graph B, Figure 2: Experimental Kr and Kr from the model are plotted on normalized scale. Using λ=3.75 leads to the best fit between curves from Equations 1 and 2. This value is then used in Equation 3 to obtain oil relative permeability.

-Graph C, Figure 2: this graph shows the experimental SS Kr and the Kr inferred from the model. While the agreement is poor, Kr curves obtained from the model are reasonable both in shape and order of magnitude.

Imbibition Kr SS Experiment on L2

The imbibition cycle is crucial since it is representative of a real waterflooding in a reservoir under production. Based on the imbibition model (drainage model + RI normalization), Kr curves can also be obtained and compared to the experimental Kr:

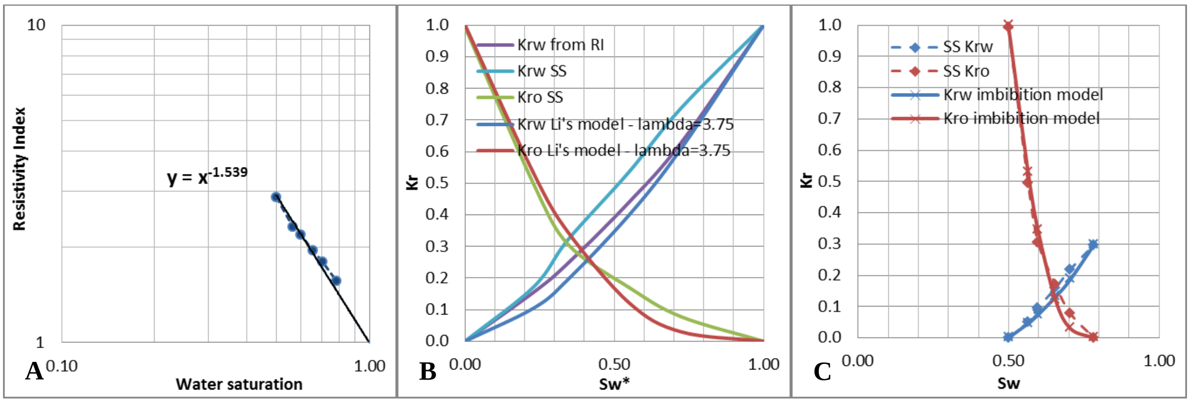

Figure 3: Data results from the imbibition Kr SS test on L2

The imbibition Archie saturation exponent n from the steady-state experiment was found higher than the one in drainage and equal to 1.54; higher n values in imbibition than in primary drainage are generally observed in the literature.

Unlike for the primary drainage, an acceptable match between the experimental SS Kr and the Kr from the imbibition model using Equations 2, 3, and 4 is obtained for λ=3.75. These results are encouraging but we still need to validate the model by running more tests on different carbonate rock types and different wettability conditions.

CONCLUSIONS

Three different core flooding techniques (porous plate, unsteady-state, and steady-state methods) with electrical measurements were conducted on a water-wet grainstone rock slab in order to derive relative permeability from electrical measurements. Li's approach was used as the base model to obtain relative permeability from resistivity in drainage. An extension of the model for imbibition was proposed and worked successfully.

The porous plate method is the most stable technique to determine both capillary pressure and resistivity index. The relative permeability curves obtained from Li's model were compared to the Brooks-Corey model and showed an acceptable agreement for the normalized relative permeabilities. But the Kr end points cannot be directly determined with this methodology. This method cannot ensure reliable Kr. Other experiments (unsteady and steady-state) were run to determine experimentally both Kr and RI curves.

The unsteady-state method with real time resistivity monitoring led to an apparent saturation exponent n which was too high for a water-wet rock. It is recommended to ensure that resistivity data are acquired with continuity and stability of the electrical current flow.

The steady-state experiment led to an n value comparable to the one from the reliable porous plate technique. A poor match between experimental Kr and Kr from Li's model was observed in drainage. A key result of this work is that the extension of the model for imbibition cycle gave an encouraging match to the experimental data; imbibition information is more crucial than drainage since it represents waterflooding in reservoir under production.

Additional experiments will be necessary to validate the generality of the overall workflow. If validated, a direct log application is thus conceivable based on combining log and core data to infer relative permeability from resistivity logs.

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