

# INVESTIGATION OF IMBIBITION SATURATION EXPONENT UNDER MIXED SALINITY ENVIRONMENT

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## ABSTRACT

An important challenge in resistivity well logging is the interpretation of electrical data to derive the water/oil saturation of an oil reservoir during sea water injection for instance. The sea water resistivity is then commonly used to obtain the water saturation from Archie's law, regardless of the potential mixing between formation brine and sea water; this is certainly valid close to the injection wellbore. However low frequency resistivity tools can have high enough depth of investigation to be affected by this mixed salinity environment. Cross-well electromagnetic (EM) resistivity method for instance, recently used to provide fluid distribution mapping at inter-well scale, can be significantly affected by the change in water resistivity during water flooding.

A core analysis program was initiated to understand the change of resistivity in mixed salinity environment using the porous plate resistivity method in imbibition cycle. Despite the known existence of hysteresis between drainage and imbibition cycles, the cementation factor  $m$  and saturation exponent  $n$ , obtained from Archie's law [1], are generally measured in the laboratory respectively before and during a primary drainage porous plate experiment with resistivity measurements. Imbibition tests are rarely performed, and when they are, no mixing effect is observed since the same formation brine is injected into the sample.

In this paper, the brine mixing effect on rock electrical properties during a porous plate imbibition test is investigated and a simple salinity model is proposed to derive the equivalent resistivity of the brine mixture for appropriate water saturation calculation.

## INTRODUCTION

In formation evaluation, unknown water salinity environment is still an obstacle to obtaining reliable reservoir saturation in a mixed salinity environment. Freeman and Fen [2] started to describe several known log analysis methods for determining reservoir saturation in a mixed water salinity environment. One of the limitations was the shallow depth of investigation of the logging tools, which were all dependent on salinity except the carbon/oxygen (C/O) method. In the last decade, many efforts were implemented to solve the mixed salinity problem. Ma *et al.* [3] gave some recommendations and fit-for-purpose logging approach using C/O logging technology for more accurate reservoir saturation monitoring and diagnosing oil displacement by brine with different salinities.

Al-Sunbul *et al.* [4] ran a pilot field test in mixed formation water salinity environment using induction tools. The multiple depths of investigation (DOI) of the slim-hole resistivity tool provided good formation resistivity data in addition to the formation water salinity determination from bottom-hole samples. Marsala *et al.* [5] showed the result of a cross-well EM technology trial project. The project objective was to map the fluid distribution and monitor the movement of the injected water; a variable formation water resistivity was used in the reservoir water saturation calculation. Ma *et al.* [6] presented a multi-well data integration approach for improved formation evaluation in a mixed salinity environment. They tackle the effect of mixing between injected fresher water and saline formation water.

In order to get a better understanding of the effect of mixed salinity on rock electrical properties, a core analysis program was initiated. It included porous plate tests with core plug resistivity measurements during imbibition cycle using two brines of different salinity. A simple salinity model is proposed to derive the equivalent resistivity of the brine mixture for appropriate water saturation calculation. This approach could be used to obtain more reliable saturations from cross-well EM technology.

## BACKGROUND

The conventional method for obtaining saturations from resistivity in a clay free rock is based on Archie's method [1]:

$$S_w = \sqrt[n]{\frac{R_o}{R_t}} = \sqrt[n]{FF} \frac{R_w}{R_t} = \sqrt[n]{\frac{R_w}{R_t} \frac{a}{\phi^m}} \quad (1)$$

Equation 1 shows the dependence of  $S_w$  to the brine salinity via the  $R_w$  parameter.

Archie's exponents are determined in the laboratory;  $m$  is measured at 100% brine saturation whereas  $n$  is obtained using the porous plate method with resistivity measurements (2-electrode configuration) made at capillary equilibrium during a primary drainage (Figure 1, left).

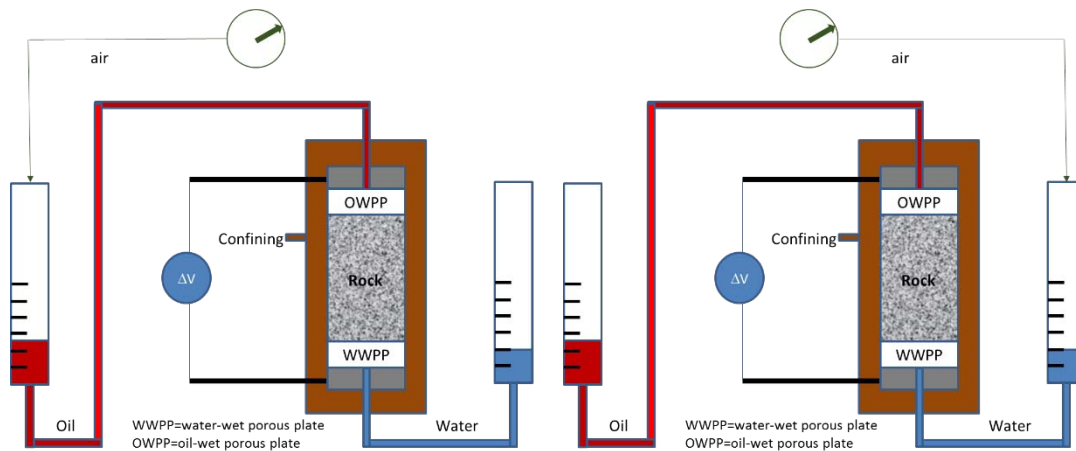


Figure 1: Porous plate and resistivity setup (drainage configuration, left – imbibition configuration, right)

The resistivity index  $RI$  curve is then plotted to obtain the drainage saturation exponent  $n_d$ , used to calculate the reservoir saturation from electrical logs. It is appropriate to calculate initial oil reserve, but imbibition saturation exponent  $n_i$  should be used to obtain a more reliable saturation from the resistivity log during water flooding (Figure 1, right).

In addition, lab data should be obtained under similar conditions to obtain more reliable saturation estimation from resistivity logs; in mixed salinity environment,  $R_t$  variation is not only due to the change in saturation and wettability, but also to the change in brine salinity. Then Equation 1 can lead to a significant error in water saturation calculation.

The porous plate resistivity method can provide information of mixing brine effect, knowing the initial formation brine volume at the end of the primary drainage and the injected brine volume during the imbibition displacement. Assuming fast brine mixing, an equivalent salt concentration  $C_{eq}$  and brine resistivity  $R_{w(eq)}$  (including Craig's approach for resistivity estimation from concentration and temperature), can be obtained :

$$a) C_{eq} = C_1 \frac{V_1}{V_t} + C_2 \frac{V_2}{V_t} \quad \text{and} \quad b) R_{w(eq)} = \left( \frac{400}{T_{ref} C_{eq}} \right)^{0.88} \quad (2)$$

Where  $C_1$  and  $C_2$  are salt concentrations of brine 1 (formation brine) and brine 2 (displacing brine in imbibition cycle) in kppm,  $V_1$  and  $V_2$  are the two brine (formation brine and displacing brine) volumes in the sample in cc,  $V_t$  is the total brine volume in cc,  $T_{ref}$  is the reference temperature for all resistivity measurements in °F.

During the porous plate resistivity experiment, water saturation  $S_w$  (frac.), 100% brine saturated rock resistivity  $R_o$  and resistivity at partial saturation  $R_t$  (in ohm.m) are measured. The saturation exponent  $n$  is obtained from the resistivity index curve  $RI$  versus brine saturation  $S_w$ . The formation factor  $FF$  measured at the beginning of the tests with the formation brine (brine 1) should be constant. Then, the equivalent 100% brine filled resistivity  $R_{o(eq)}$  and resistivity index  $RI_{eq}$  when two brines are mixed during a porous plate resistivity experiment can be obtained from Equations 3:

$$a) FF = \frac{R_o}{R_w} = cte \Rightarrow b) R_{o(eq)} = FF * R_{w(eq)} \quad \text{then} \quad c) RI_{eq} = \frac{R_t}{R_{o(eq)}} \quad (3)$$

Combining equations (2a), (2b) and (3c):

$$RI_{eq} = \frac{R_t}{FF \left( \frac{400}{T_{ref} (C_1 V_1 + C_2 V_2)} \right)^{0.88}} \quad (4)$$

Since concentration and volume of each brine are known during each test, Equation 4 can be used to calculate the equivalent resistivity index  $RI_{eq}$ .  $RI_{eq}$  versus brine saturation  $S_w$  is then plotted to obtain the imbibition saturation exponent  $n_i$  from Archie's regression.

In this study, two twin Berea sandstones were tested for resistivity (2-electrode configuration and 20 KHz of frequency) using the porous plate method in primary

drainage and imbibition cycles. During the imbibition cycle, desaturation of one sample was performed using same initial formation brine 1, whereas desaturation of the second sample was performed using a less saline brine 2 (for mixed salinity assessment).

## ROCK AND FLUID PROPERTIES

A clay free and high porosity sandstone (Berea) was tested in this program (Table 1).

Sample Id	$\rho_g$ (g/cc)	$\phi$ (%)	PV (cc)	$K_g$ (mD)	$K_{kl}$ (mD)	$FF$	$m$
S-A	2.65	25.0	10.6	698	691	16.5	2.02
S-B	2.65	25.0	11.0	592	585	16.4	2.01

Table 1: Rock properties of the two twin sandstones

As expected, the dry porosity-permeability and electrical properties at 100% brine saturation of these two samples were found to be similar.

An iso-paraffin oil (Isopar L) was used as non-conductive phase. Two brines (NaCl equivalent) of different salinity were prepared:

- Brine 1 or formation brine (200 kppm NaCl,  $R_{w1}=0.05$  ohm.m) for initial rock saturation of both samples and injected brine for imbibition of sample S-A,
- Brine 2 or injected brine (50 kppm NaCl,  $R_{w2}=0.16$  ohm.m) for the imbibition of sample S-B, simulating sea water injection for instance.

## EXPERIMENTAL RESULTS

The porous plate resistivity test was performed using four capillary pressure  $P_c$  steps (up to 20 psi maximum  $P_c$ ). Confining pressure of 800 psi was applied (ambient pore pressure and room temperature of 68°F). Brine resistivity was measured at the same room temperature. Resistivity data points were taken at transient state and capillary equilibrium.

As expected, irreducible saturation  $S_{wi}$  and saturation exponent  $n_d$  were found to be comparable for the twin plugs (Table 2).

Sample Id	$S_{wi}$ (%)	$n_d$ (equilibrium)	$n_d$ (all data points)
S-A	23.8	1.94	1.93
S-B	22.9	1.95	1.94

Table 2: Primary drainage data results

Resistivity at capillary equilibrium or at transient state lead to similar values of saturation exponent  $n_d$ .

The imbibition cycle was immediately started at the end of the primary drainage. The

spontaneous imbibition was not separately tracked but hidden in the forced imbibition. Since resistivity was the main objective, imbibition saturation exponent  $n_i$  was obtained from transient resistivity data during a one single  $P_c$  step of 5 psi. Thereby, the imbibition capillary pressure curves are not obtained.

The transient imbibition resistivity index data points were plotted versus water saturation  $S_w$  to derive the imbibition saturation exponent  $n_i$  (Figure 2). In sample S-A, the same brine 1 was used to displace oil whereas brine 2 was used to displace oil in sample S-B. Equation 4 was used to correct for mixed salinity effect on sample S-B.

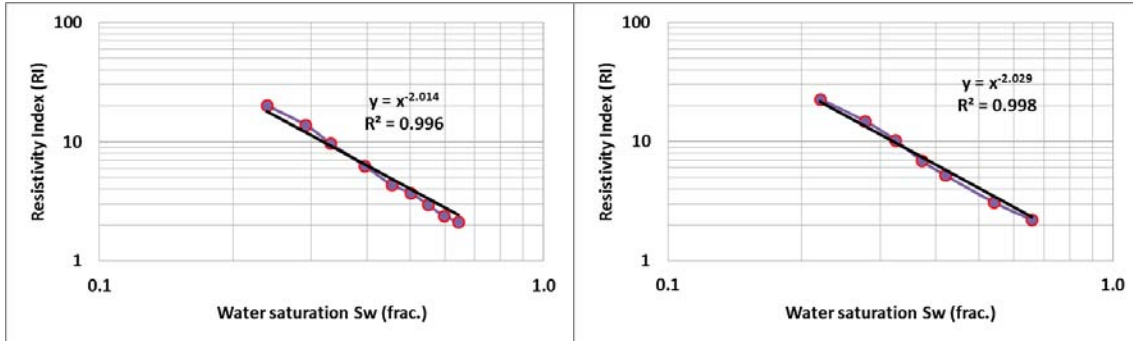


Figure 2: Transient imbibition  $RI$  curves for sample S-A (left) and for sample S-B (right)

Final water saturation  $S_w$  for both samples was very close ( $S_{w1}=64.3\%$  and  $S_{w2}=65.7\%$ ); they were confirmed by post Dean-Stark cleaning. The saturation exponent  $n_i$  obtained from sample S-B ( $n_i=2.03$ ) with mixed salinity correction using Equation 4 was found to be close to the one from sample S-A ( $n_i=2.01$ ) where same formation brine was injected. For sample S-B, if  $R_w$  from equation 1 was kept constant and equal to either  $R_{w1}$  (formation brine resistivity) or  $R_{w2}$  (displacing/injected brine), saturation exponent  $n_i$  would have been respectively higher and lower as shown in Table 3.

$R_w$ (ohm.m)	$R_t$ (ohm.m)	$\phi$ (%)	$m$	$n_i$	$S_w$ (%)
$R_w(\text{mixed})=0.08$	2.97	24.95	2.01	2.03	65.7
$R_{w1}=0.05$	2.97	24.95	2.01	2.15	54.8
$R_{w2}=0.15$	2.97	24.95	2.01	1.16	84.5

Table 3: Imbibition data results for sample S-B

Using Equation 1 with  $a=1$ , the difference in saturation exponent  $n_i$  according to brine resistivity can lead to a significant error in water saturation calculation if the correcting model in Equation 4 is not applied (Table 3). Using formation brine or injected brine resistivity can respectively overestimate or underestimate the reservoir oil saturation.

Nevertheless, Equation 1 can still be used to derive reservoir water saturation in a mixed salinity environment if the equivalent brine resistivity  $R_{w(eq)}$  obtained from the mixing law in Equation 2 is updated while water flooding the reservoir. Another advantage of

this laboratory protocol is that a more realistic residual oil saturation will be obtained during an EOR program where low salinity brine is injected for instance.

## CONCLUSION

To get a better understanding of the effect of mixed salinity on rock electrical properties, a core analysis program including porous plate tests with resistivity measurements during the imbibition cycle using two brines of different salinity was performed. A simple salinity model was proposed to derive the equivalent resistivity of the brine mixture for an appropriate water saturation calculation. Even if the lab method does not fully represent a real flooding cycle in the reservoir, the proposed mixing model can help in assessing and correcting the error induced by the change in overall brine resistivity.

It was shown that not taking into account the contrast in resistivity between the formation and the injected brines during water flooding can lead to a significant error in the estimation of oil-water saturations. In a real reservoir environment, knowing the initial formation brine saturation and its resistivity, in addition to the volume of injected brine of known resistivity in the region of investigation of the cross-well EM method (based on frequency/depth of investigation), this approach could be used to obtain more reliable inter-well saturations. Additional studies such as wettability and heterogeneity effects on the validation of the mixing model, in addition to a final field test, are required.

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