HYSTERESIS OF THE RESISTIVITY INDEX IN BEREA SANDSTONE

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Abstract The paper reports an investigation of the influence of saturation history on resistivity of oil–wet and water–wet Berea sandstone. Four–electrode resistivity measurements were conducted on the sandstone plugs with varying brine saturation. The resistivity was measured continuously during the saturation cycles: primary drainage, imbibition, and repeated drainage. The data from 10 plugs indicated that the saturation history did not influence the brine saturation/resistivity index relationship of water–wet cores, while on oil–wet cores, the saturation history strongly influenced the relationship. In the oil–wet cases, the saturation exponent, n, was about three and had a slightly increasing trend during the primary drainage cycle. During imbibition it increased strongly to about six and then fell back to a value of about three to four during the secondary drainage.

INTRODUCTION

Determination of water saturation of oil–bearing formations is based on resistivity measurements in situ and Archie's law:

$$RI = \frac{R_t}{R_o} = \frac{1}{S_w^n}$$

where RI is defined as the resistivity index. R_o and R_t are, respectively, the resistivities of 100 per cent brine–saturated rock and of the same rock partially saturated with brine. S_w is brine saturation, and n is the saturation exponent.

The value of the saturation exponent is about 2 for clean water–wet cores (Archie 1942). Several laboratory tests have demonstrated that the saturation exponent should be adjusted according to the wettability of the rock (Whiting, 1953; Sweeney and Jennings, 1960; Mungan and Moore, 1968). It can reach values of 10 or more for uniformly oil–wet cores with low brine saturations. However, electric well logs of natural systems have seldom found reservoir oil formation resistivities which approach such extreme values. Swanson (1980) has given an example of the apparent contradiction between results from laboratory measurements and from well logs. The data of his work on restored cores, believed to have mixed wettability, demonstrated oil–wet characteristics from waterflood behavior, whereas their electrical behavior essentially remained the same as for water–wet systems.

In search for an answer to this paradox, both the wettability and the experimental procedure should be in accordance to the *in situ* reservoir conditions. It is well known that capillary hysteresis is demonstrated when changing saturation direction and that the hysteresis has a strong influence on the relative permeability and capillary pressure behavior (Osoba *et al.*, 1951; Killins *et al.*, 1953). For a given wettability condition, the resistivity of a rock is not a unique function of the brine saturation. It also depends on the distribution of the saturating fluids. Furthermore, this distribution is controlled by saturation history. Generally, the saturation history is referred to as both the manner applied to obtain the desired fluid saturation and the saturation cycle, drainage or imbibition.

Several authors have taken this hysteresis phenomenon into account in core resistivity studies. Lewis *et al.* (1988) indicated that the saturation exponent is substantially different under drainage and imbibition. Earlier work to check this phenomenon in porous media was reported by Mungan and Moore (1968). They did not, however, observe any hysteresis in the brine saturation–resistivity index relationship on packed teflon spheres during the cycle of drainage and imbibition. The resistivities at the same saturations obtained during different saturation directions, were thought to be a non–equilibrium phenomenon and not a hysteresis. Most researchers have adopted one saturation direction, usually drainage, to study resistivity behavior on oil–wet cores without paying special attention to the hysteresis. The recent work made by Longeron *et al.* (1989) showed that the saturation direction had a strong effect on the relationship. The importance of understanding the role of hysteresis of resistivity on core measurements can not be overemphasized for improving interpretation of well logging.

The purpose of this work has been to investigate the hysteresis effect on brine saturation/resistivity index relationship using a steady-state flooding method on water-wet and oil-wet Berea cores.

EXPERIMENTAL

Material

Core plugs with a diameter of 3.7 cm were drilled out from two blocks of standard Berea sandstone. The rough ends of the cores were cut by diamond saw to be 12 cm long. The plugs were cleaned with Soxhlet extraction by acetone, methanol, toluene, and methanol subsequently. Then the cores were dried in oven at 100°C for 24 hours. Porosity and permeability of the two sandstone blocks were 24.3 per cent, 780 mD and 19.0 per cent, 150 mD, determined by routine analysis. Some of the dried cores were ready to be used in the experiment as water-wet samples. The remaining of the dried cores were rendered to become oil-wet by treating them with a solution of 2 volume per cent Quilon-S in distilled water (Maini *et al.*, 1986). The wettability of the cores were tested with Amott wettability method (Amott, 1959). The results are shown in Table 1. We did not check the stability of the wettability properties after the experiment.

The fluids used in the experiment were kerosene, filtered trough a column of silica, and a 36 g/l NaCl solution. The densities of the kerosene and the brine were 0.775 and 1.018 g/cc at 21°C, respectively.

Apparatus

Arrangement of the apparatus used in the experiment is schematically shown in Figure 1. The essential advantage of the apparatus was the use of a digital balance to continuously monitor the change of the core saturation. Careful adjustment of teflon tubes and wires ensured the balance sensitivity from being disturbed. Normally, the readings could be taken with an accuracy of ± 0.01 g. In this way the error which would arise from disrupting tests and thus violating the continuous

TABLE 1 Core wettability properties.

Core	*Water displacing oil*			*Oil displacing water*		
	Water free imb. (ml)	*Oil forcing water* (ml)	*Water Amott index*	*Oil free imb.* (ml)	*Water forcing oil* (ml)	*Oil Amott index*
Oil–wet	0	6	0	1	1.4	0.42
Water–wet	3.9	0.4	0.91	0	4.5	0

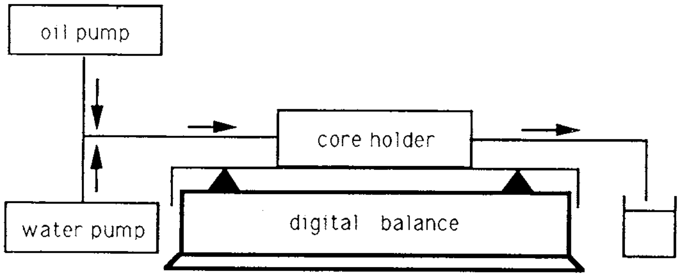

FIGURE 1 Set–up of measurement system.

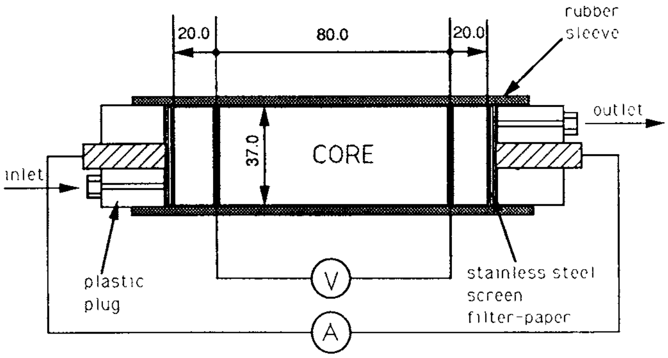

FIGURE 2 Scheme of resistivity cell.

state were avoided. The brine saturation error resulting from the dead volume of the core holder was less than 3%.

The electrical resistance of the cores was measured by the four-electrode method. The instrument was a four channel-frequency response analyzor, Solartron 1254. An AC power source of 500 Hz and 200 mV was imposed on the system. The current was determined by measuring the voltage drop over a reference resistor of 1004 Ω in series with the core. The maximum current density in the core was 0.14 A/m^2. The voltage drop over the core was measured by means of the other three channels. The electrode arrangement is shown in Figure 2. This arrangement gave us the possibility to look at the saturation distribution along the core. Likewise, we could analyse the influence of the contact resistance of the two-electrode measurement. Details about these effects are beyond the scope of this article and will be presented elsewhere.

Procedure

The dried core samples were saturated with oil or brine under 2–4 Pa vacuum for at least 3 hours. The effective porosity for liquid was obtained by weighing.

The saturated core was then assembled together with rubber sleeve, cramps, and steel rack. Resistivities were measured at different saturations by changing the volumetric flow ratio of oil and brine under a total flow rate of 5 ml per minute. Each saturation point was reached by pumping 5–6 pore volumes of liquids. At the final saturations, irreducible water saturation or residual oil saturation, the flow rate was 7.5 ml per minute and 10–15 pore volumes of oil or brine were pumped through. The pumps were then stopped. After 10–15 minutes the resistivity readings were stable and we assumed that an equilibrium of the oil and brine distribution had been reached. The readings were taken in the course of 2–3 minutes. The readings were usually very stable with an absolute deviation of 0.1%. The resistivity measurements for one saturation direction was completed in one day. The measurements for the reversed saturation direction were continued the next day, after about 18 hours. The experiments were performed at room temperature 21±1°C.

Of the 10 runs, the runs 2–3, 3–1, 3–2, and 3–3 were conducted with three cycles, i.e. primary drainage, imbibition, and finally secondary drainage. Of the remaining 6 cores, 5 runs were made with two saturation direction cycles, i.e. primary drainage and imbibition. In run 1–3 an attempt was made to measure the resistivity on an oil–wet core initially saturated with water. Because this procedure is an unstable displacement, it was impossible to obtain stable resistivity readings.

RESULTS AND DISCUSSION

The data presented in Figures 3 and 4 show the hysteresis effect on brine saturation–resistivity index behavior for water–wet and oil–wet Berea sandstone.

The tests on Figures 3 were conducted on water–wet Berea cores initially saturated with 100% brine. The cores in Figure 3, a and b, were tested with two saturation directions, primary drainage and imbibition, and the cores in Figure 3, c and d, with three saturation directions, i.e. with an additional secondary drainage. The tests on the four cores did not give any evidence to capillary hysteresis effect on core resistivity behavior as a function of saturation direction. Within the range of measurement error, the curves of reverse saturation direction followed the former trace. The resistivity index curves for the four runs demonstrated a typical behavior of clean water–wet cores in which Archie's saturation exponent, n, has a value of about 2.

Figure 3, e and f, show the results from water–wet cores initially saturated with oil instead of water. Although there was a redistribution of oil during the imbibition process where water displaced oil from the

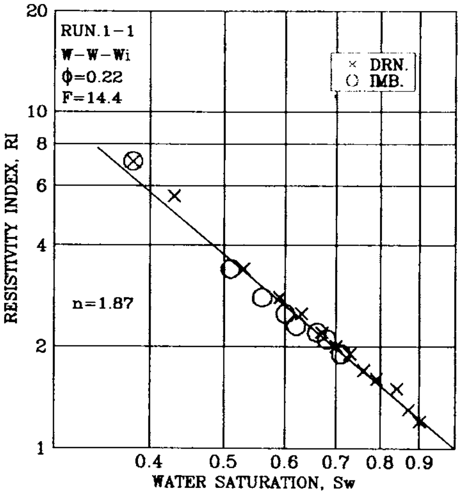

FIGURE 3a Hysteresis effect in water-wet core.

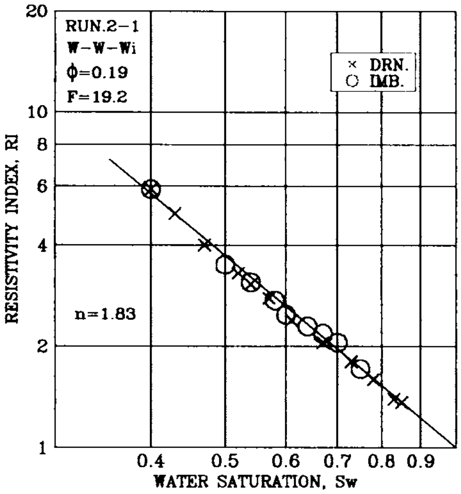

FIGURE 3b Hysteresis effect in water-wet core.

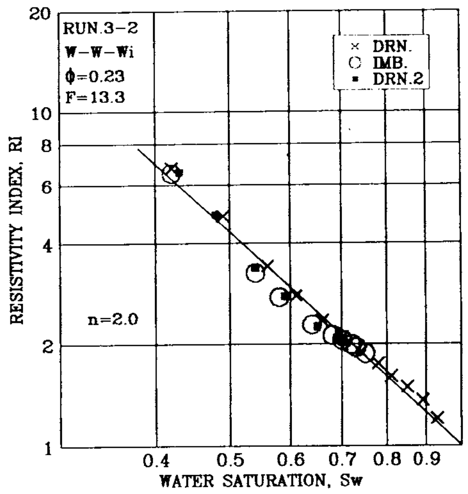

FIGURE 3c Hysteresis effect in water–wet core.

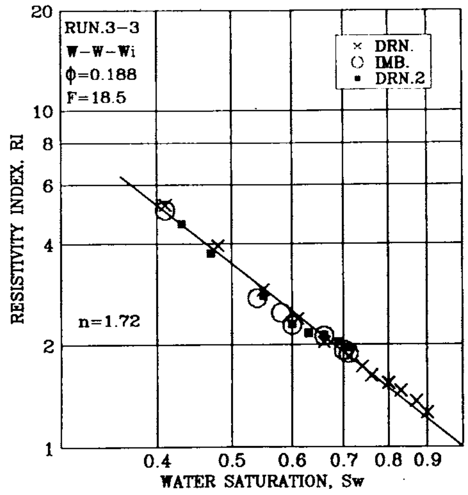

FIGURE 3d Hysteresis effect in water–wet core.

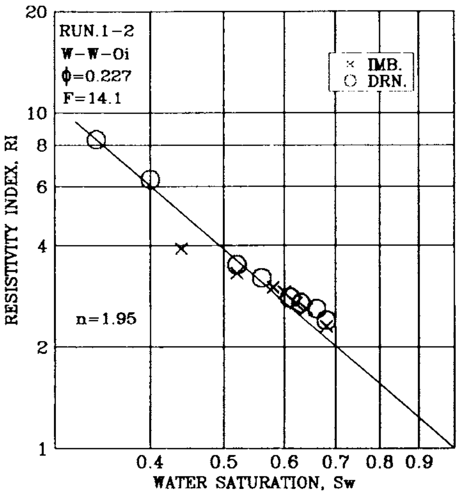

FIGURE 3e Hysteresis effect in water-wet core.

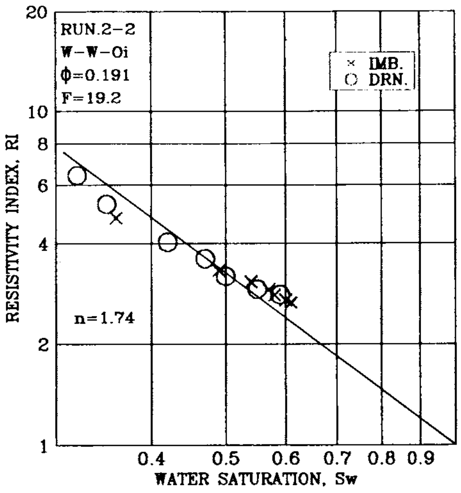

FIGURE 3f Hysteresis effect in water-wet core.

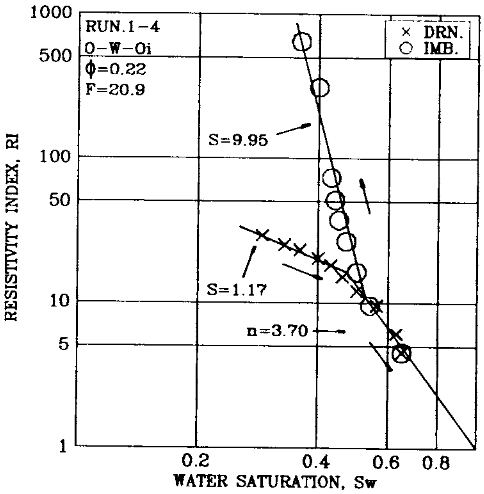

FIGURE 4a Hysteresis effect in oil–wet core.

water–wet grain surface, the equilibrium was reached in 15 minutes. The two curves show a water–wet behavior with saturation exponents of 1.95 and 1.74. It seems that the two curves have a break at about $S_w = 0.58$ with two different slopes on either sides.

The results from the six water–wet cores showed that the brine saturation/resistivity index relationship was not influenced by the saturation direction under the the steady–state flooding procedure. The resistivity of a water–wet core seems to be a unique function of the brine saturation and independent of the saturation cycle. This indicates that the distribution of the brine in the pore space is not affected by the saturation history when the brine is the wetting phase.

The curves in Figure 4 represent the electrical behavior of oil–wet cores under saturation cycles. The tests were carried out on cores initially saturated with oil. In contrast to the results from water–wet cores, the resistivity behavior depends strongly on the saturation history. From the data of the three tests, an average saturation exponent for the primary drainage between 2 and 3 is found. For imbibition and secondary drainage, however, the exponent reaches the value of about 10. The resistivity behavior during secondary drainage in Figure 4, b

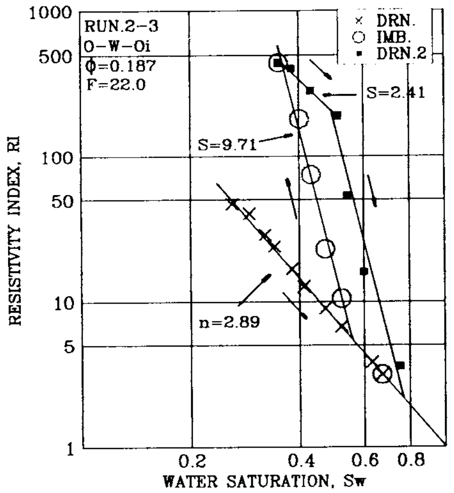

FIGURE 4b Hysteresis effect in oil-wet core.

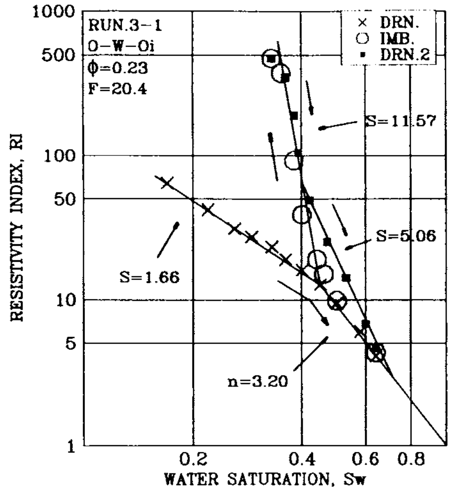

FIGURE 4c Hysteresis effect in oil-wet core.

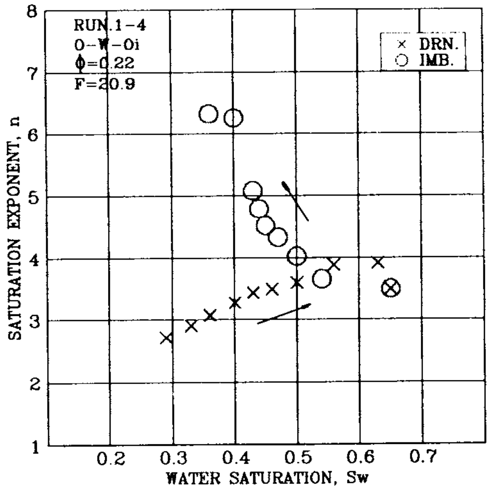

FIGURE 5a Hysteresis effect on the saturation exponent.

and c, shows that the brine drops that were trapped during the imbibition remain trapped and therefore the passage for current is blocked by oil. The trapping seems to be irreversible.

Figure 5 shows the hysteresis phenomenon on the saturation exponent, n, recalculated from the data in Figure 4.

Anderson (1986) has given a instructive analysis of the wettability effect on Archie's saturation exponent. He pointed out that two factors can cause the resistivity, and hence n, to rise more steeply in an oil-wet case: the trapping of a portion of the brine by oil and the formation of dendrites or fingers of brine.

To explain the hysteresis of resistivity in oil-wet cores, we postulate that the two factors, trapping and fingering, play a different role in different saturation directions. Without doubt, the influence of the two factors exists throughout the whole saturation cycle. It is likely that the fingering is a dominant action for the saturation exponent increase during the primary drainage, while under imbibition and secondary drainage the trapping is dominating.

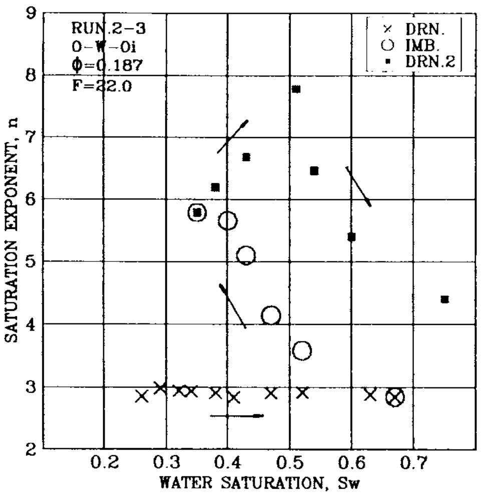

FIGURE 5b Hysteresis effect on the saturation exponent.

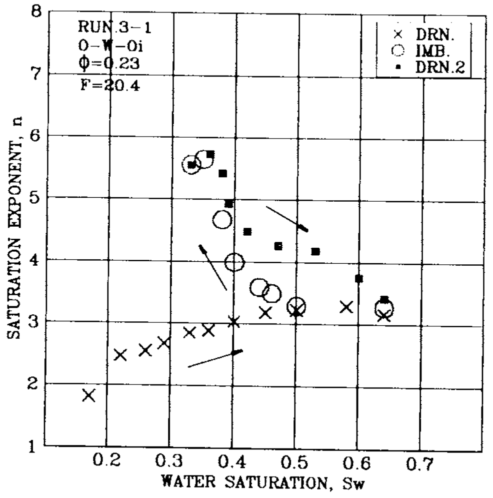

FIGURE 5c Hysteresis effect on the saturation exponent.

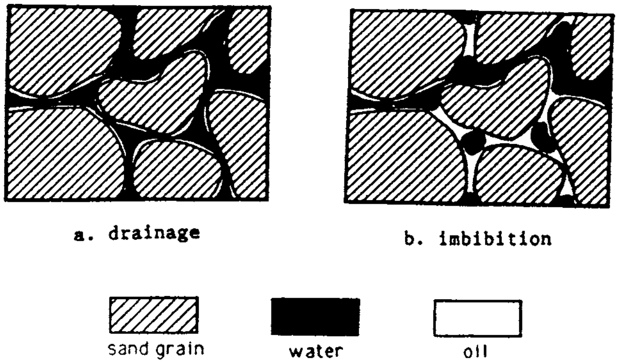

FIGURE 6 Distribution of oil and water in oil–wet cores during a saturation cycle.

It can be imagined that under primary drainage, since the brine saturation increases, the brine invades into smaller pores from larger ones. While the water saturation increases, more and more fingers are developing from the "main streams" of the brine which initially filled the largest pores in the start of the drainage. Some fingers will connect to each other and make long electrical paths. Some of them will stop at dead or pseudo–dead–end pores (Figure 6a). However, in water–wet cases the brine are connected in all directions to form a conductive network. Therefore the saturation exponent in the oil–wet case will be higher than in the water–wet one.

For the imbibition direction, as the brine saturation decreases, the brine "main streams" begin to shrink. Therefore more and more fingers are cut off from "main streams", being separated by oil or oil film, especially at the pore throats (Figure 6b). The cut fingers become trapped, isolated drops of brine which do not take part in the conduction of electricity. The isolated brine will cause the exponent, n, to increase more rapidly than during the primary drainage.

For the secondary drainage, the slope of resistivity index curve indicates that the isolated brine drops do not merge into the "main streams" during the following flooding.

CONCLUSIONS

The results of this work may give us some clues to improve resistivity measurements in laboratory and well logging interpretation. The following conclusions can be drawn from the study:

1. In water-wet cores, with the brine as the wetting phase (dispersion phase), the distribution of the brine in the pore space is not affected by the saturation history. We believe that the resistivity is a unique function of the brine saturation. Archie's law is valid for water–wet condition and the saturation exponent is about 2, regardless of saturation history.
2. In oil-wet cores, with the brine as the non-wetting phase (dispersed phase), the distribution of the brine in the pore spaces depends on the saturation history. In this situation, Archie's law is not valid. The presented data show that the brine saturation/resistivity index relationship is not a unique function. The saturation exponent, being about 2–3 for the primary drainage, increases strongly for the following imbibition and the secondary drainage, reaching a maximum value of about 8.
3. To ensure compatibility between laboratory data and well logging data, besides making the core wettability identical to the formation condition, it is necessary to choose a reasonable saturation procedure to imitate the real saturation history in the logged formation zone.

ABBREVIATIONS

W–W	water–wet
O–W	oil–wet
W–W–Wi	water–wet core initially saturated 100% with water
O–W–Oi	oil–wet core initially saturated 100% with oil
DRN.	drainage
IMB.	imbibition
DRN.2	secondary drainage
S	curve slope
F	formation factor

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PERMEABILITY