HYSTERESIS OF THE RESISTIVITY INDEX IN UNCONSOLIDATED POROUS MEDIUM

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Abstract Four-electrode resistivity measurements were conducted on water-wet, oil-wet, and intermediate wet quartz sandpacks for 3–7 saturation directions with a steady state flooding procedure. The data from 3 runs indicated that there was a resistivity index hysteresis loop in the S_w-I_R plot during saturation cycles on each sandpack. The hysteresis behavior substantially depended on the sand surface wettability and saturation history. The more oil-wet, the more hysteresis in resistivity index. In the water-wet sandpack, a moderate hysteresis of the resistivity index was found. In the middle wet and oil-wet pack, a large hysteresis was demonstrated between saturation and desaturation. The recommendation from this study is that the saturation history influence should be taken into account in laboratory resistivity measurements.

INTRODUCTION

Resistivity measurements in special core analysis are crucial to electrical log interpretation. It is well known that core wettability has a profound effect on the Archie's saturation exponent(Anderson, 1986; Longeron *et al.*, 1989). Our previous work has shown that the core resistivity is not only a function of brine saturation and wettability but also depends on the saturation history(Jun-Zhi and Lile, 1990, 1991, 1992).

The saturation history-dependent hysteresis phenomenon in resistivity measurements is called *resistivity index hysteresis*. This hysteresis, like capillary pressure and relative permeability hysteresis, results from the irreversibility of the distribution of two(or more) immiscible phases saturating the porous medium during drainage and imbibition. The hysteresis behavior depends on pore geometry, interfacial tensions, and experimental conditions.

To obtain an accurate oil saturation from well-logging interpretation, one should try to duplicate the reservoir conditions in laboratory resistivity measurements. Core cleaning, flooding manner used in saturation and desaturation, electrode pattern, etc. can affect the resistivity precision directly or indirectly.

This paper reports the influence of saturation history on electrical conductivity behavior in an unconsolidated porous medium, crushed quartz packs. To avoid confusion, the following terminology is used in this paper:

Saturation direction: brine or oil saturation is increasing or decreasing. It is referred to as drainage or imbibition by rule.

Saturation cycle: a complete saturation cycle consists of a drainage displacement followed by an imbibition flooding.

EXPERIMENT

The dimensions of the sandpacks and the electrode pattern used in the measurements are shown in Figure 1. Quartz sand, crushed from a large quartz block and then sieved with Tyler mesh -65 to +100, was used as unconsolidated porous medium. The porosity of the sandpacks was 0.434. The quartz sand was strongly water-wet. The water-wet quartz was made to be strongly oil-wet by treating it with a solution of 1.5 volume per cent dimethyldichlorosilane in toluene. Water-wet and oil-wet sandpacks were made of the water-wet and the oil-wet quartz respectively. The intermediate wet sandpack were made from a mixture of water-wet and oil-wet quartz, 50% of weight for each.

The total flow rate was 8 ml per minute in the steady state displacement.

The details about fluids, brine and oil, instruments, experiment conditions, test set-up and resistivity measurement procedure applied in the investigation can be found elsewhere(Jun-Zhi and Lile, 1991).

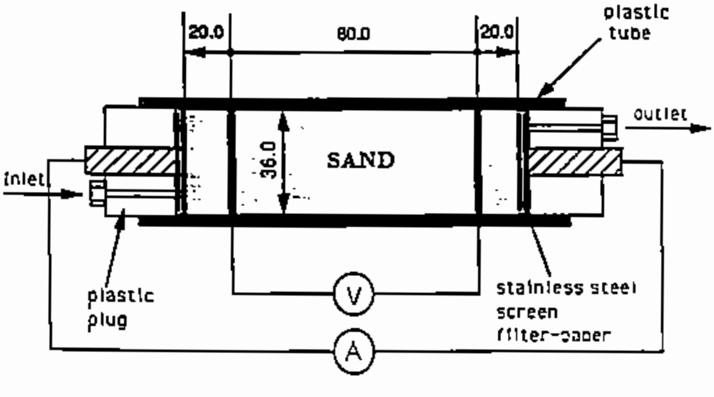

FIGURE 1 Scheme of sandpack for resistivity measurements.

RESULTS AND DISCUSSION

Resistivity Index Hysteresis

Figures 2 through 7 show that a hysteresis of resistivity index exists in all sandpacks with various wettabilities: strongly water-wet, intermediate wet, and strongly oil-wet. It is obvious that as the porous medium surface becomes more oleophilic, the resistivity index increases and the hysteresis phenomenon becomes more pronounced.

Figure 2 demonstrates that a closed resistivity index hysteresis loop was formed during three saturation directions in a water-wet sandpack initially saturated 100% with brine(W-W-Wi). In this case the second drainage resistivity index curve closely matches the first one. This means that one can get a unique resistivity value for a special water saturation in a definite saturation direction, drainage or imbibition, during saturation cycles through the whole flooding history. For all saturation directions at the W-W-Wi condition appreciable hysteresis can not be seen when the brine saturation is larger than about 0.5.

The characteristics of the hysteresis loop is shown more clearly in Figure 3 by curves in which the data points and the coordinate grid are omitted.

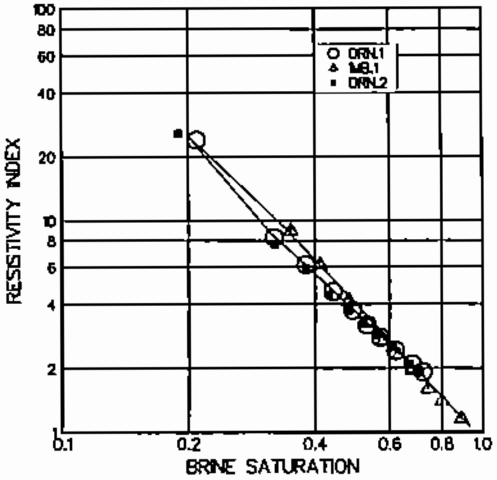

FIGURE 2 Resistivity index hysteresis in water-wet sandpack initially saturated 100% with brine(W-W-Wi).

Figures 4 and 5 show the data obtained from an oil-wet sandpack initially saturated 100% with oil(O-W-Oi) and an intermediate wet sandpack initially saturated 100% with brine(M-W-Wi). In O-W-Oi, resistivity measurements were started from the lowest brine saturation because of the initial saturation with oil. The two figures show that the electrical behavior during the first drainage has its own special behavior which differs from the following imbibition and subsequent drainage. After the first drainage, the imbibition and the drainage resistivity index follow a fixed loop track, as shown in the diagrams.

The resistivity index hysteresis loops in O-W-Oi and M-W-Wi sandpacks are drawn in Figures 6 and 7 which are matched with data in Figures 4 and 5. The loops started from the first imbibition because the first drainage resistivity index curve does not follow the loops. Note that the difference in resistivity exists between all saturation direction pairs over the whole saturation range.

To examine the hysteresis phenomenon microscopically, the *channel flow* concept(Craig, 1971) in porous media is helpful. When the brine saturation changes from decreasing to increasing, more brine is pumped into the oil-filled pores and new water channels are created.

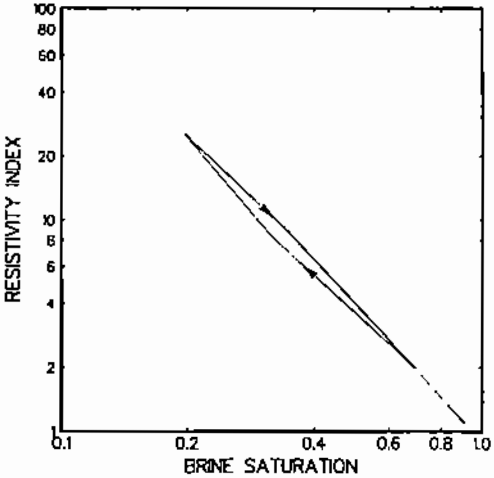

FIGURE 3 Resistivity index hysteresis loop in W-W-Wi sandpack.

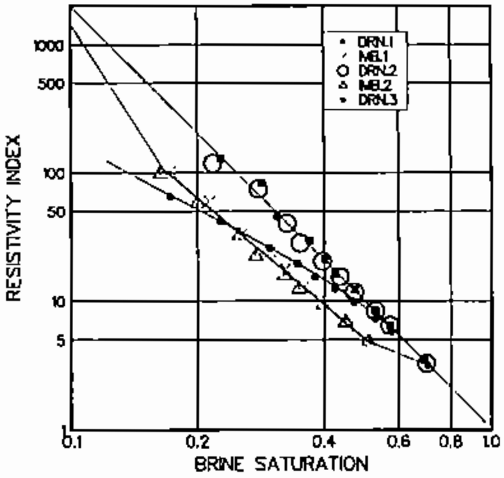

FIGURE 4 Resistivity index hysteresis in oil-wet sandpack initially saturated 100% with oil(O-W-Oi).

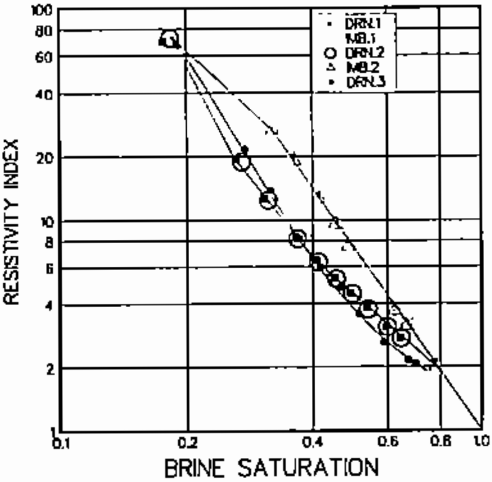

FIGURE 5 Resistivity index hysteresis in middle-wet sandpack initially saturated 100% with brine(M-W-Wi).

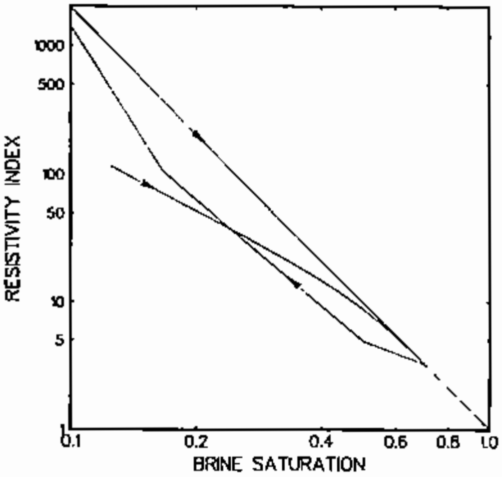

FIGURE 6 Resistivity index hysteresis loop in O-W-Oi sandpack.

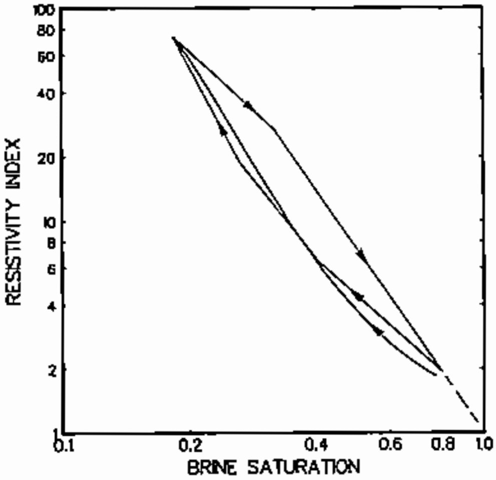

FIGURE 7 Resistivity index hysteresis loop in M-W-Wi sandpack.

A new channel does not become a continuous electrically conductive path until it becomes a part of the interconnected network which offers a path for electricity to pass. The isolated brine makes the resistivity being higher than normal in this manner, disobeying Archie's law, and the largest gap can be found in the hysteresis loop at the lowest brine saturation end. As the brine saturation increases, the proportion of isolated brine decreases, which results in the hysteresis decrease at higher brine saturations.

First Drainage Resistivity Behavior in Non-water-wet Cores

The most important resistivity data are the drainage resistivities which are useful for the petrophysicists to evaluate hydrocarbon volume in situ.

In figure 4 we have shown the strange behavior of the first drainage resistivity index on oil-wet sandpack initially saturated with oil. It is significant for logging engineers to analyse these data to guide their log interpretation because the electrical behavior in this case is analogous to that in the flushed zone of an open hole. The flushed zone is subjected to the same drainage as the first drainage in these mea-

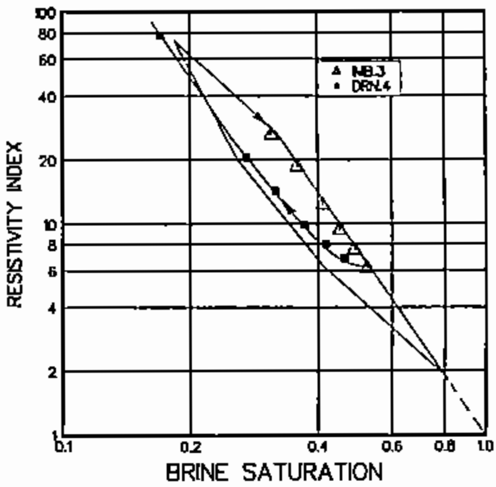

FIGURE 8 Half-way saturation cycle resistivity index hysteresis in M-W-Wi sandpack.

surements. Generally, the flushed zone resistivity is obtained after the oil formation has been drilled through. Once the formation is entered, drilling mud filtrate pushes away crude oil to some distance, i.e., the virgin oil formation undergoes a first drainage in its development history. It is interesting that the first drainage resistivity index curve has its own special behavior which is different from both the drainage and the imbibition ones in the hysteresis loop. Some uncertainty may be introduced into reserve estimation of an oil formation if one uses a saturation exponent which has been derived from an unrealistic saturation direction resistivity measurement in the laboratory.

Obviously, the first drainage resistivity index curves in the O-W-Oi and M-W-Wi sandpacks demonstrate that as brine saturation increases or decreases, more brine becomes isolated so that the slope of the curves becomes larger, i.e., the Archie's saturation exponent increases during the primary saturation direction. After the first drainage a definitive hysteresis loop is formed, that means the amount of isolated brine in sandpack has reached a dynamic equilibrium and it only depends on the saturation direction for a given wettability.

Resistivity Hysteresis for Half-way Saturation Cycle

Figure 8 shows the half-way saturation cycle resistivity index hysteresis in M-W-Wi sandpack. The third imbibition stopped on the half-way to return back to start the forth drainage. The data of resistivity from the half-way measurements show that once the saturation direction was changed the resistivity index could not follow the hysteresis loop immediately. There was some delay in time before the data joined the loop track.

CONCLUSIONS

The following conclusions are made from this study:

1. There are resistivity index hysteresis loops in the S_w-I_R diagrams for crushed quartz sandpacks of varying wettability: water-wet, oil-wet, and intermediate wet, during saturation cycles under steady state flooding.

2. The stronger the oil wetting is in the porous medium, the larger hysteresis in the resistivity index is found.

3. For water-wet quartz sandpack initially saturated 100% with brine, the hysteresis loop starts from the first drainage. For oil-wet quartz sandpack initially saturated 100% with oil and middle-wet quartz sandpack initially saturated 100% with brine, the hysteresis loop starts from the first imbibition.

4. The first drainage resistivity behavior in M-W-Wi and O-W-Oi quartz sandpacks demonstrates a special behavior that is very different from the following hysteresis loops in the same sandpack.

ABBREVIATIONS

W-W-Wi =water-wet sandpack initially saturated 100% with brine
M-W-Wi =middle-wet sandpack initially saturated 100% with brine
O-W-Oi =oil-wet sandpack initially saturated 100% with oil
DRN.1 =primary drainage
IMB.1 =primary imbibition
DRN.2 =secondary drainage
IMB.2 =secondary imbibition

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