FLUID FLOW AND ELECTRICAL RESPONSE OF A VUGGY ROCK SLAB MODEL

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ABSTRACT

We report the results of a study on the fluid flow and electrical properties of a vuggy rock sample. This study used a new experimental apparatus, called the rock slab flooding system, specially designed to visually observe fluid distribution within a vug during two-phase flow (brine and oil). In addition, a four-electrode system was used to monitor the resistivity of the rock during drainage and imbibition cycles. The effect of frequency on Archie's parameters, namely cementation factor *m* and saturation exponent *n,* was also investigated.

Two rock slabs were cut from a water-wet Indiana limestone block. One slab was kept as it was (original block) while the other was drilled at its center to simulate the presence of a cylindrical vug (vuggy block). Windows placed at both extremities of the vug provided a seal while making it possible to visualize the distribution and flow of fluids in the vug. Cementation factor was measured on both model blocks at different frequencies. A video camera recorded the distribution of fluids inside the vug. Real time resistivity was continuously recorded during primary drainage and imbibition of the vuggy model.

The visual cell helped to indicate the differences in flow behavior between drainage and imbibition of the vuggy model. This observation was then correlated to the electrical response. An apparent saturation exponent n^* estimated during the unsteady-state two-phase flow showed frequency dependence in drainage. The non-Archie behavior and the low values of n^* were attributed to the combination of brine-filled micro-pore network, small electrical contribution of the vug to the bulk rock resistivity and flow conditions. All these findings are important for the interpretation of resistivity logs in vuggy carbonate reservoirs.

INTRODUCTION

The complexity of electrical responses can lead to significant uncertainties in saturation estimation from resistivity logs. This is especially true for carbonate reservoirs, where the pore structure can be very complex and where the properties of the rock surface can vary across the same reservoir. The combination of both effects leads to variations of the Archie parameters, the cementation factor *m* and the saturation exponent *n*, generally taken equal to 2 for convenience.

Fleury (2002), Fleury et al. (2004), Padhy et al. (2006) or Han et al. (2007) have recently indicated that the electrical response of vuggy rocks was still not well understood. An experimental study on fractured rocks performed by Standler et al. (2009) showed that the resistivity index increased with a decrease in frequency. All these findings are critical for the estimation of water saturation in fractured or vuggy carbonate reservoirs. In this paper, we studied the effect of a single vug on the electrical properties of a water-wet Indiana limestone rock during a two-phase flow (brine/oil), investigating the frequency effect on real time resistivity measurements, so on the called "apparent" saturation exponent n^* estimated during a two-phase flow.

SAMPLES and METHODS

Background

Resistivity of rocks is known to be sensitive to saturation history and wettability as well. Archie's laws (1942) express an empirical correlation between electrical resistivity index and brine saturation. The combination of the two Archie's laws is used for water saturation estimation in logs interpretation:

$$S_w = \left(\frac{R_w}{R_t \times \phi^m} \right)^{\frac{1}{n}}$$

Where R_t is the resistivity of the rock, R_w is the brine resistivity, ϕ is the porosity, m and n are respectively the cementation factor and the saturation exponent measured in the laboratory.

This law is well established on clay-free siliclastic and homogeneous sandstones. In carbonate reservoir, rocks are heterogeneous at different scales (micro, meso, and macro-porosity) and have wide range of wettability making the resistivity index curves behave in a non-Archie way.

Porous media samples and fluids

MICP and NMR T_2 measurements were first performed on an Indiana limestone rock:

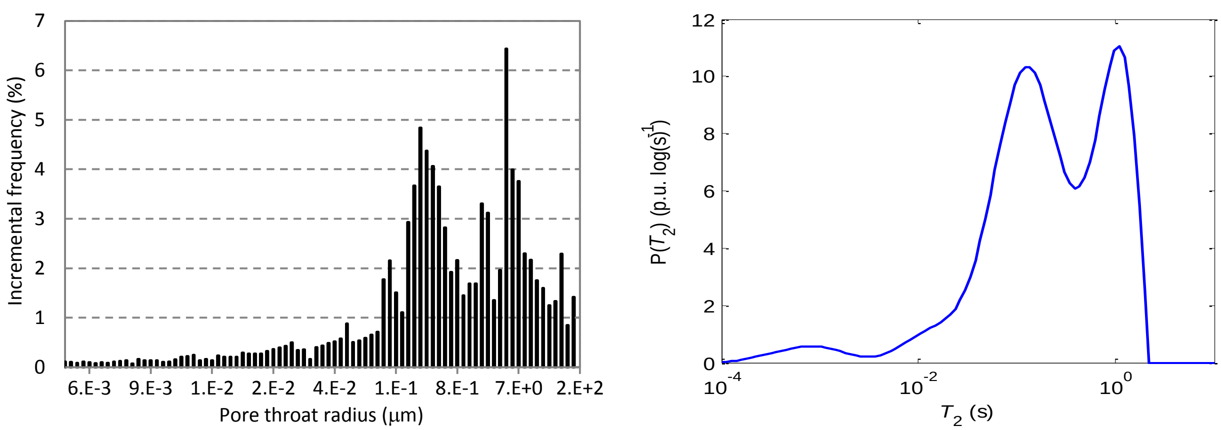

Figure 1: MICP and NMR T_2 of the Indiana limestone rock.

MICP and NMR T_2 distribution of fully brine saturated core plug show that Indiana limestone sample has a bimodal porosity system. MICP data results indicate that more than 50% of the pore space is microporosity. It was confirmed by confocal microscopy analysis of a thin section.

In addition to these measurements, the water wettability of the rock matrix, initially conventionally cleaned by Soxhlet extraction method, was confirmed by the Amott-Harvey and USBM wettability indices determined by centrifuge technique ($WI_{A\text{-}H\ \&\ USBM} > 0.65$).

Equivalent formation brine with high salinity was prepared. Paraffinic oil (Soltrol 130) was used as oil. Fluid properties are found in Table 1:

	Density (g/cc) @ 25^{o}C	Viscosity (cp) @ 25^{o}C	R_w (ohm.m) @ 21.5^{o}C
Brine 200Kppm NaCl	1.14	1.55	0.047
Soltrol 130	0.75	1.60	X

Table 1: Fluid properties.

Experimental setup and procedure

Two rock slab models (6cm length, 3.7cm height, and 2.3cm thickness) were cut from the Indiana limestone block: one slab was kept as reference while the other one was drilled at its center to simulate the presence of a cylindrical vug (1cm diameter). Two transparent windows were placed at both extremities of the vug to enable a direct observation of the fluids distribution. Two stainless steel end platens were placed at the two ends of the rock slab for fluids injection, production and also as current electrodes. A 4-contact electrodes configuration was used to monitor the real time rock resistivity during the unsteady-state flow. A video camera was placed in front of the vug to record the time dependence of the vug filling during the two-phase flow. The vuggy model and a schematic of the experimental setup are shown in Figure 2:

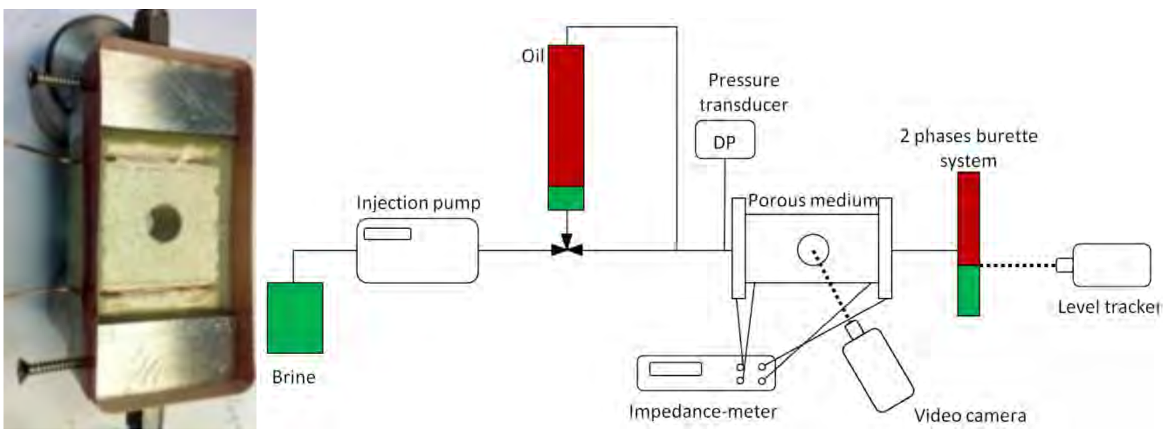

Figure 2: Vuggy rock slab model and experimental setup.

The rock slabs were first conventionally cleaned, dried, vacuumed and saturated with brine. Porosity was calculated for both untouched and vuggy models using the weighting method. Cementation factor *m* and permeability to brine *k* were then measured. Primary drainage and imbibition cycles of both models were performed at a constant flow rate *Q* of 0.2 and 0.1cc/min respectively. Differential pressure, cumulative fluids recovery and rock resistivity R_t were continuously measured while the camera recorded the fluids distribution in the vug.

The generalized Bond number Bo*, important parameter to understand the occurrence of instabilities, was found to be positive: the flow was assumed to be stable. This information is important because the apparent saturation exponents *n** deduced from real time resistivity measurements during unsteady-state flow tends to decrease under stable flow (Liu, 2010).

RESULTS

Rock properties such as porosity ϕ, permeability to brine *k* and cementation factor *m* at 4 different frequencies were measured on the untouched rock slab and on the vuggy one (Table 2):

	k (mD)	ϕ (%)	*m*@100Hz	*m*@1KHz	*m*@10KHz	*m*@100KHz
Matrix slab	26.8	16.2	2.1	2.1	2.1	2.1
Vuggy model	47.0	19.1	2.3	2.3	2.3	2.3

Table 2: Rock properties of the untouched and vuggy models.

The vug embedded in the porous matrix leads to an increase of the porosity, permeability and cementation factor. Increase of *m* for the vuggy system is consistent with the literature: Focke and Munn (1987) showed that the presence of large pores, like vugs, could have a little electrical contribution to the bulk conductivity of the rock, even in the connected brine-filled case. A good agreement was found between the cementation factors *m* measured on the untouched matrix model and on a twin core plug using a conventional ambient resistivity system: this validates the experimental setup and the electrical measurements. No frequency effect on *m* was observed.

In the following, only the 2-phase flow data results of the vuggy model are presented.

Primary drainage - Oil is first injected at a flow rate of 0.2cc/min.

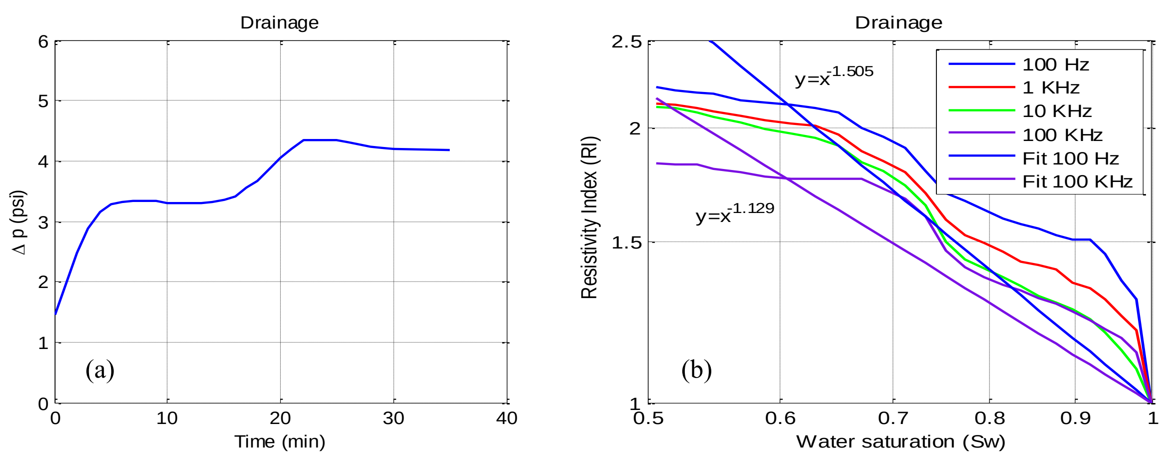

Figure 3: Differential pressure (a) and resistivity index curves (b) during primary drainage.

The differential pressure *DP* curve (a) is the direct signature of the presence of the vug. At the beginning of the injection, oil penetrates the rock matrix, leading to an increase of *DP*. Then a plateau is observed when the oil front reaches and fills the vug. Once completely filled, the front re-invades the remaining matrix, leading to an increase of *DP*, until the breakthrough. Pairoys et al. (2003) explained this feature as the result of the non wetting oil preference to invade the vug where the capillary pressure is negligible in comparison with the capillary pressure in the matrix.

The resistivity index *RI* (b) is also dependent on the sequential oil invasion process of the vuggy model. A resistivity stabilization or plateau is observed at all frequencies during the filling of the vug. It is also important to note that an increase of frequency tends to lower the resistivity: Sandler et al. (2009) observed similar results on fractured rocks. The irreducible water saturation is found to be high (S_{wi}=0.505%) due to the large amount of brine-filled micro-porosity.

RI curves show a non-Archie behavior of the vuggy model at all frequencies. A power law is used to fit the *RI* curves: low apparent saturation exponents *n** are obtained under the USS flow. The increase of frequency leads to a significant decrease of *n**. As a result, a very low value of *n** is found at 100KHz of frequency. The *RI* plateau and high frequency experiments tend to lower the apparent saturation exponent n^*. Moreover, Herrick et al. (1996) showed that low n values are caused by at least three features: layers with different capillary properties, continuous micro-porosity and surface conduction. In this study, the two first features can also explain very low values of n^*.

The video camera placed in front of the vug was really helpful to understand and correlate the process of vug filling with the resistivity and *DP* responses:

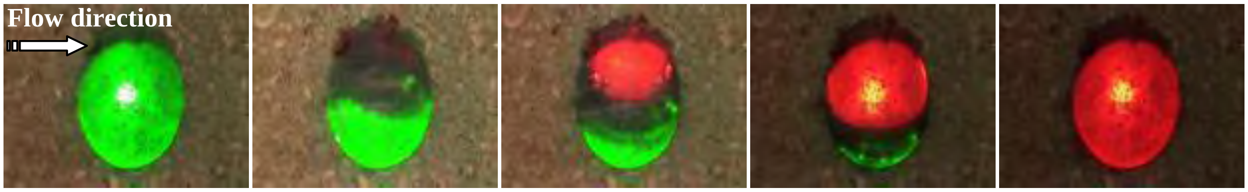

Figure 4: Vug filling during primary drainage (brine in green and oil in red).

Fluids were dyed to get a visual contrast between them (brine in green and oil in red). When the oil front reaches the vug, oil droplets appear on the left half surface of the vug (injection side), move up and coalesce to form a bigger bubble at the top. The vug was completely filled by oil in less than 10 minutes, confirming the sequential filling process explained before.

Imbibition - After the primary drainage, brine is injected at a flow rate of 0.1cc/min.

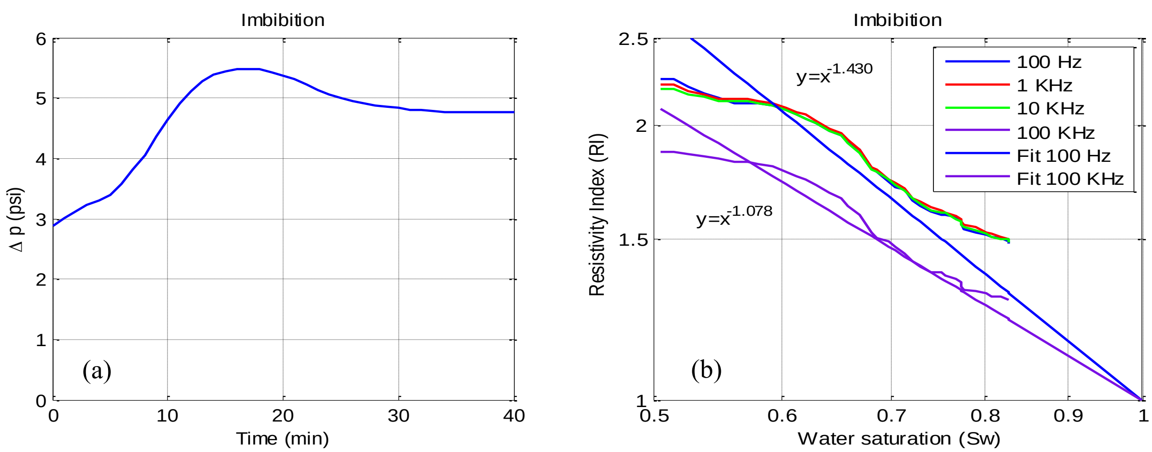

Figure 5: Differential pressure (a), resistivity index (b) during imbibition.

Unlike the drainage process, no plateaus are observed on the *DP* and *RI* curves: this is due to predominant capillary forces in the rock matrix, leading to the simultaneous fluids displacement in the matrix and in the vug. The impact of this flow displacement process on the electrical measurements does not represent a significant contribution to the non-Archie behavior (no *RI* flattening). All curves are parallel and except for the highest frequency (100KHz), there is no frequency effect on the apparent saturation exponent n^*. As explained for the primary drainage, the low values of n^* are due to the combined effects of the small electrical contribution of the vug, the high electrical contribution of the brine-filled micro-porosity and the regime of the flow. The results motivate further study to understand the effect of frequency above tens of KHz in imbibition.

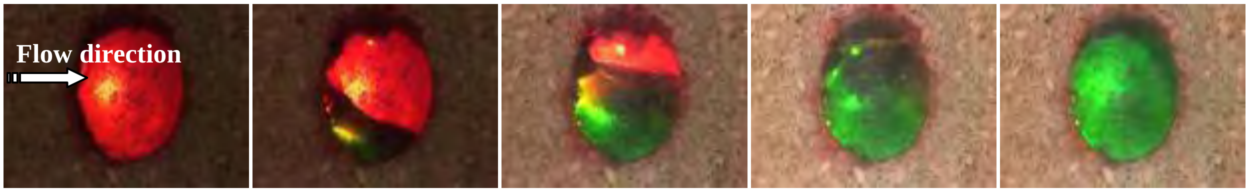

Figure 6: Vug filling during imbibition (brine in green and oil in red).

The capillary suction of the water-wet rock matrix leads to an early breakthrough (BT = 17min) accompanied by a long tail of production. The complete brine filling of the vug (Figure 6) was observed after breakthrough, confirming the simultaneous fluids displacement process.

A similar two-phase flow study, using same fluids and flow rates, was performed on the same rock without vug showing a less pronounced non-Archie behavior in drainage, a less pronounced hysteresis between drainage and imbibition *RI* curves, and no frequency effect on n^*.

CONCLUSIONS

In this study, a resistivity cell allowing a direct visualization of fluids distribution in an artificial vug was developed and used to understand the two-phase flow behavior and to monitor the real time resistivity response of a water-wet vuggy model at different frequencies. The non-Archie behavior of the vuggy model observed on the *RI* curves was found to be more pronounced in drainage than in imbibition due to the sequential fluids displacement process in drainage. Further, the increase of resistivity during the filling of the vug by oil was minimal, resulting in a flattening of the *RI* curves. This flattening effect combined with the large amount of brine-filled microporosity, acting as a parallel conductive path, led to very low values of apparent saturation exponent n^* estimated under USS flow. In addition, the *RI* versus S_w curves showed frequency dependence in drainage: at given water saturation, an increase of frequency is accompanied by a decrease of resistivity on the vuggy model. This finding is important for log interpretation, notably because electrical logs are currently performed at multiple frequencies.

REFERENCES

[1] G.E. Archie, "The Electrical Resistivity Log as an Aid in Determining some Reservoir Characteristics", Trans. AIME, vol. 146, p.54, 1942

[2] J.W. Focke, D. Munn, "Cementation Exponents in Middle Eastern Carbonate Reservoirs", SPE 13735, SPE Formation Evaluation Journal, Volume 2, Number 2, 1987

[3] D. C. Herrick, W. D. Kennedy, "Electrical Properties of Rocks: Effects of Secondary Porosity, Laminations and Thin Beds" SPWLA Conference Paper, 37 Annual Logging Symposium, 1996

[4] F. Pairoys, D. Lasseux, H. Bertin, "An Experimental and Numerical Investigation of Water-Oil Flow in Vugular Porous Media", SCA2003-20, Society of Core Analysts, Pau, France, 2003

[5] M. Fleury, "Resistivity in Carbonates: New Insights", SCA2002-28, Society of Core Analysts, Monterey, USA, 2002

[6] G.S. Padhy, M.A. Ionnidis, C. Lemaire, M. Coniglio, « Measurement and Interpretation of Non-Archie Resistivity Behavior in Model and Real Vuggy Carbonates », SCA2006-11, Society of Core Analysts, Trondheim, Norway, 2006

[7] M. Han, M. Fleury, P. Levitz, "Effect of the Pore Structure on Resistivity Index Curves", SCA2007-34, Society of Core Analysts, Calgary, Canada, 2007

[8] J. Sandler, Yuzhang Li, R.N. Horne, Kewen Li, "Effects of Fracture and Frequency on Resistivity in Different Rocks", SPE 119872, Society of Petroleum Engineers, Amsterdam, The Netherlands, 2009

[9] Z. Liu, "The Dependence of Electrical Resistivity, Saturation and Saturation Exponent on Multi-Phase Flow Instability", Thesis presented to the Graduate School of Clemson University, USA, December 2010