Wireless acquisition for Resistivity Index in Centrifuge – WiRI: A new method to estimate Archie's Law Parameters

Quentin Danielczick[1*], *Pierre Faurissoux*[2], and *Benjamin Nicot*[2]

[1]SeaOwl Energy Service, on behalf of TOTAL S.A Editorial Department, 64000 Pau, France
[2]TOTAL S.A, CSTJF – Experimentation Interpretation Synthesis Department, 64000 Pau, France

Abstract. During the last decades, computing power, digital techniques and instrumentation have been drastically improved. In the petrophysical field, these technological advances help to improve data quality, reduce costs and experimental time. Water saturation determination is key for the knowledge of hydrocarbon in place. It is often estimated from resistivity measurements using Archie's equations. Archie's parameter "n" is calibrated from laboratory measurements. The conventional method, known as Porous Plate technique, is based on resistivity measurements on samples with uniform saturation profiles. This method is time consuming. In a previous paper we proposed a faster method: "Ultra-Fast PcRI" (based on the combination of three techniques: centrifugation, Nuclear Magnetic Resonance Imaging (NMR) and resistivity profiling). This allows the use of a non-uniform profile along a sample to determine the n exponent faster, however it increases the amount of sample handling. Here we present a low-cost and low-handling method to obtain capillary pressure curves and saturation exponent using onboard resistivity measurements in operating centrifuge with wireless communication. The centrifuge is used to generate a saturation profile in the sample. During the rotation, resistivity profile is measured with an "in house" developed multi-electrode equipment and recorded wirelessly. The produced volume is recorded with a camera. Finally, a numerical inversion is applied on the Archie's equation to obtain the n exponent. This method is applied together with the GIT (Green Imaging Technologies) patented capillary pressure method and therefore provide capillary pressure and resistivity index values in parallel. The numerical treatment needed has been tested and validated on synthetic saturation profiles. Also, it has been successfully tested on outcrop and reservoir samples in gas-water drainage process.

1 Introduction

"Mr Archie's paper suggests an experimental attack for expanding and improving the interpretation technique of electrical well logging. Any contribution of this nature that increases its effectiveness is of great value to the petroleum industry." This sentence, pronounced by S. W. Wilcox is written in the discussion section of the famous paper of Gustavus Archie, Electrical Resistivity Log as an Aid in determining Some Reservoir Characteristics [1].

The objective of the proposed method is to contribute to speed-up the evaluation of the Archie's parameters "m" and "n" in laboratory. These two parameters are required to convert resistivity measurements into saturations and thus, to evaluate hydrocarbon in place. Cementation exponent "m" is easily measured in laboratory by measuring rock resistivity at 100 % brine saturation. Obtaining the saturation exponent "n" consists in plotting the resistivity index (RI) versus water saturation (S_w). Exponent n is the slope of this log-log curve. Historically, the Porous Plate (PP) technique, which assumes a homogeneous saturation profile along the samples, allows the recording of the resistivity-saturation couple one by one. However, the experimental duration for the achievement of the capillary equilibrium is substantial.

Solutions to accelerate the determination of the n exponent have been proposed by Fleury [2-3], Bona *et al.* [4] and more recently by Faurissoux *et al.* [5]. Our experiences with the latest showed great results, however one of the drawbacks of any imaging-based method is still on: the amount of laboratory handling.

In order to deal with this specific problem, the present paper proposes a low handling and fast method to determine both capillary pressure curve and saturation exponent. This method is intended to be a complementary tool to the existing measurements (such as centrifuge) or to provide a fast n determination (for early log interpretation). Assuming the validity of Archie's law and the homogeneity of analysed rocks, the entire process takes between few hours and few days in gas-water drainage, from loading rock samples into the centrifuge

* Corresponding author: quentin.danielczick@total.com

up to determining the n exponent and the Pc curve. The WiRI (**Wi**reless **R**esistivity **I**ndex) method consists in acquiring a resistivity profile along a sample during centrifugation and transmitting the data wirelessly to the acquisition system (outside the centrifuge) for real time data treatment.

2 Equipment and procedure set-up

2.1 General description

Experiments were conducted using tailor made equipment coupled with a Beckman J6 centrifuge system. The centrifuge rotor can accommodate up to 4 buckets. The rock samples are loaded into core-holders and inserted into the buckets, as shown in Fig. 1.

The core-holders (adapted to 45 mm length and 30 mm diameter samples) are operating at ambient pressure and temperature. To minimize creep and deformation in the centrifuge, the technology combines a cylinder of Polyether Ether Ketone (PEEK) and a cylinder of stainless steel. Each core holder contains current injection and potential electrodes at the top and bottom of the sample, plus 8 radial electrodes (2 mm thick with 3 mm insulated space between the electrodes). The cylinder in PEEK (in contact with the sample) supports the electrodes and acts as an insulator between them. The stainless-steel cylinder is placed around the peek to perform an axial stress and a mechanical radial clamping to ensure good contact between the sample and the electrodes. This device measures 9 impedances at 1kHz frequency to acquire a resistivity profile along the sample. The 4 contacts resistivity method presented by Garrouch and Sharma [6] is implemented.

All the electrodes are wired to a multiplexer and an antenna located on the rotor (Fig.1). In order to perform a measurement, both power and communication are needed. In this case, the difficulty is the transmission of power and information between rotor and stator. Durand and Lenormand [7] proposed a rotating contact solution. In this work this is achieved with a wireless 5 volts induction system and RFID Reader. This system delivers power to the antenna and allows communication at the same time.

During the experiment, the produced effluents are collected in a tube. A centrifuge camera is used to measure the production volume (V_{prod}) over time. Home-made software (designed with VeePro© software) monitors the wireless impedance and the production.

Note that further developments are ongoing to perform tests at high pressure and temperature.

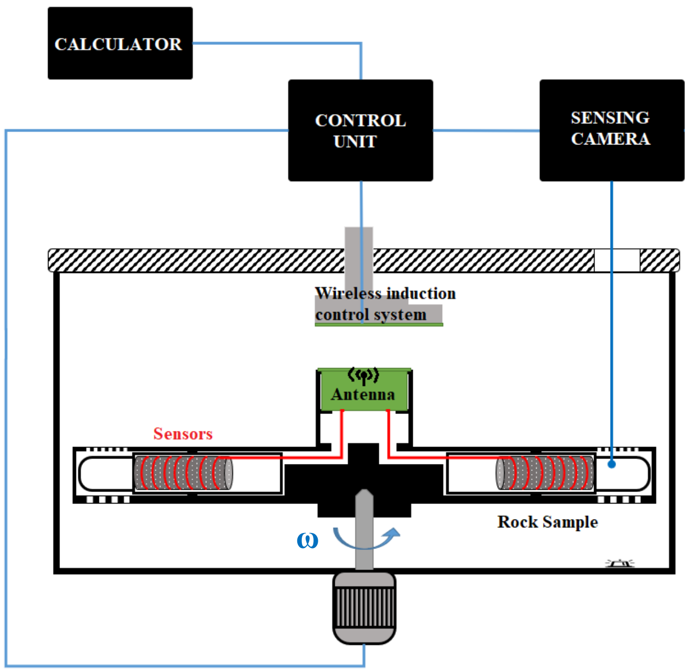

Fig. 1. Wireless Resistivity measurements embedded in centrifuge.

2.2 Rock samples and fluids

Two sample, one Estaillades plug and one sandstone reservoir core of 30 mm diameter and 45 mm length are used for the WiRI experiments. In order to characterize the samples, a Conventional Core Analysis program coupled with Nuclear Magnetic Resonance (NMR) imaging was conducted. The Estaillades sample was analyzed in a dry and fully saturated (80 g/l NaCl brine) states and the reservoir rock plug was analysed in a fully saturated state (13g/l Formation Water (FW)). Table 1 summarizes the basic properties of the two samples and NMR results are presented in Fig.2.

The study was done on both monomodal and bimodal pore size distribution, respectively for the reservoir rock and the Estaillades one, as shown in Fig 2.a with the T2 relaxation time distribution. In addition, a fully saturated NMR profile was performed in order to validate qualitatively the homogeneity of the porosity along the samples (Fig 2.b).

Table 1. Base properties of the analysed samples (20 °C)

Sample	Porosity	Grain Density	K_{klink} perm
Estaillades E1	25.7%	1.89 g/cc	200 mD
Reservoir Rock	19.5 %	2.66 g/cc	180 mD

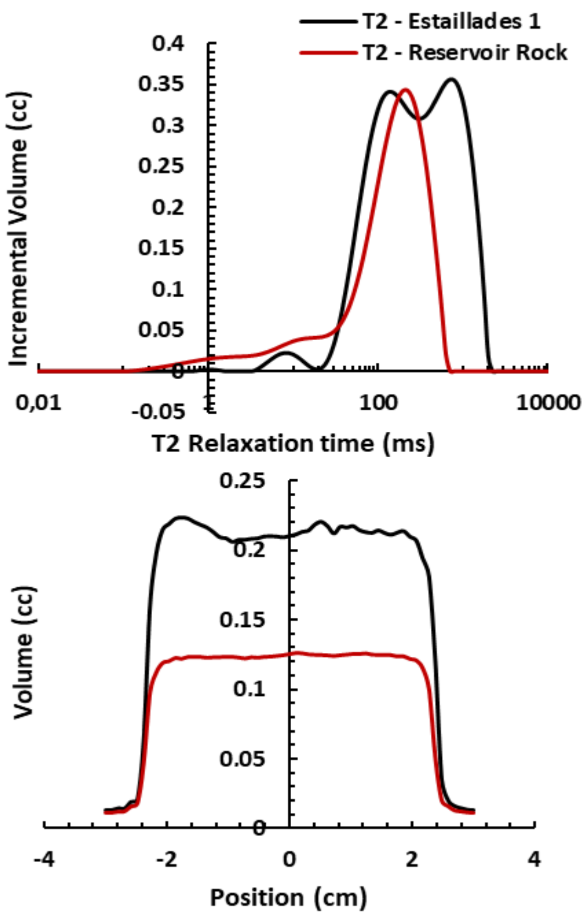

Fig. 2. a- T2 relaxation time **b-** NMR Volume profile @Sw=100% for Estaillades outcrop in black and reservoir rock in red.

Note that in this study, only gas water drainage cycle has been performed. Table 2 summarizes properties of used fluids.

Table 2. Base fluid properties (20 °C)

Sample	Viscosity (cP)	Density (g/cc)
Gas (air)	0.018	0.001
Brine for E1	1.450	1.052
Brine for Reservoir core	1.080	1.007

2.3 Procedure

The experimental protocol for WiRI measurements is presented below. It is important to notice that step 1 to 5 represent conventional characterization, whereas specific WiRI steps begin on step 6.

Sample characterization:

1) Clean the core by sequence of toluene and iso-propanol injections; Drying by nitrogen flushing, followed by heating in the oven at 80°C.

2) Measure gas permeability and Helium porosity (ϕ).

3) Saturate with synthetic brine ($S_w = 100\%$) and determine pore volume (V_p) from weight difference between saturated and dry mass divided by brine density.

Fully saturated properties:

4) Determine brine resistivity (R_w) at 20°C.

5) Mount the core in the multi-electrode device, and measure resistivity at S_w=100% (R_0). Verify the resistivity homogeneity. R_0 must have the same value (or at least close ones) for each slice (between pair of electrodes). Resistivity heterogeneity and possible outcomes are discussed in the discussion section.

Determination of primary drainage Capillary Pressure and Resistivity Index (PCRI) curves:

6) Spin the core in the centrifuge in drainage mode to enforce a capillary pressure (P_c). V_{prod} will reach a plateau. The process can take several hours up to few days (depending on the permeability of the rock sample and the fluids used for drainage). After the stabilization, the P_c profile induced by centrifuge is calculated using the equation in the Fig.3.

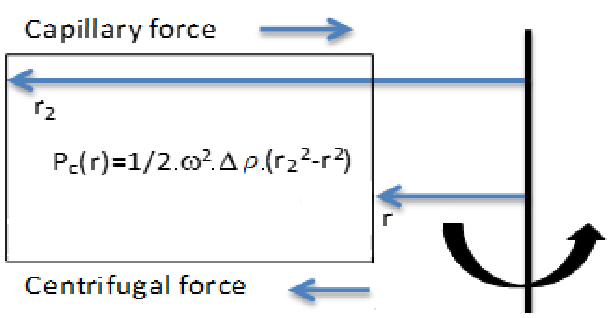

Fig. 3. Capillary Pressure equation for drainage in centrifuge with ω the angular frequency, Δρ the difference between the densities of the fluids, r2 the maximum radius and r the radius where Pc is calculated. This Figure was introduced by Faurissoux et al. [5]

7) Obtain production volume by the camera and record it across the drainage process. A representation is given on Fig.4 with crosses representing the "end point production" for each step.

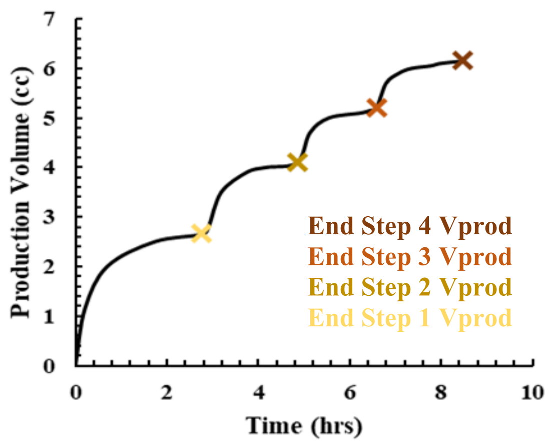

Fig. 4. Schematic representation of Production volume curve.

8) Acquire the resistivity profile (R_t) corresponding to the V_{prod} by the wireless technology. Fig.5 represents multiple R_t profiles measured with the multiple sensors along the sample. The profile resolution is electrode-spacing dependent.

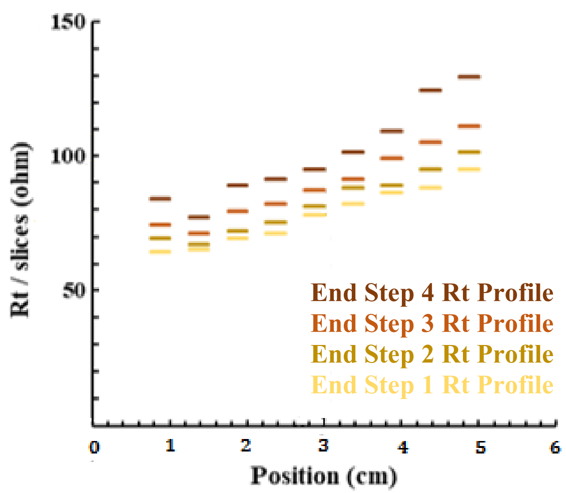

Fig. 5. Schematic representation of Multi-electrode device resistivity measurements in centrifuge.

9) Loop step 6 for next centrifuge speed (and next P_c profile) and iterate to populate multiple end V_{prod} and multiple R_t profiles.

10) Convert Resistivity measurements into Resistivity Indexes (RI) with eq.1

$$RI = \frac{R_t}{R_0} \tag{1}$$

11) Use an optimization process to solve an inverse problem that consists on determining the n exponent only with RI in eq.1 and end V_{prod} of each centrifuge step.

2.4 Optimization problem

In this case, two assumptions are necessary in order to perform the optimization: the sample should be homogenous and must follow the Archie's Law (eq.2).

$$R_t = \frac{a\,R_w}{\Phi^m {S_w}^n} \tag{2}$$

Whereas R_w, Φ and cementation exponent m are determined with conventional methods, the saturation exponent "n" and the S_w profile are determined at the same time by an optimization process and multiple local R_t measurements along the sample.

At each equilibrium stage, water production, "End Step V_{prod}" (crosses Fig4) is subtracted from V_p (the pore volume) to determine water volumes (V_w) still in place in the samples with eq.3.

$$V_w = V_p - V_{prod} \tag{3}$$

For each centrifuge step, noted j, Archie's Law is used to build an estimator (eq.4) of the conductive fluid (water) volume inside the rock. This estimator (noted $\widehat{V_w}$) is dependent on the saturation exponent n and Resistivity Index measured between each slice i. In the eq.4 below, N_{Slices} is the number of RI slices (determined by the number of electrodes on the device).

$$\widehat{V_{w_j}}(n) = \frac{Vp}{N_{Slices}} * \sum_{i=1}^{N_{Slices}} \left(\frac{1}{RI_i^{\frac{1}{n}}} \right) \tag{4}$$

1) *Parameter: Saturation exponent n*

The optimization problem consists in finding the n exponent that best fits the measurements. Optimization begins by the initialization of a presumed saturation exponent n.

2) *Optimization problem: monodirectional (there is only one parameter (n) to solve this problem). The problem is described by minimising the objective function O – eq. 5*

$$\boldsymbol{O} = \sum_{j=1}^{N_{Steps}} [V_{wj} - (\widehat{V_{wj}}(n))]^2 \tag{5}$$

Determining the least squares between our estimator and the measured value is a conventional method to find a solution (it is called identification problem). N_{Steps} represents the number of centrifuge speed steps used to obtain V_{wj} measurements.

3) *Optimization interval: (0; +∞]*

The formulation of the problem was chosen to define the n exponent as strictly positive.

4) *Available methods: derivative free methods or direct methods.*

To find the minimum of the objective function, methods based on the calculation of the gradient (derivative methods) or based on direct search methods (such as the bisection method) are used. In both cases, the principle is the evaluation of the objective function for a first "initial guess" of the n value (for example "n=2") and repeat function or gradient evaluations until the minimum is found. Many algorithms to estimate Archie-Parameters as Core Archie-Parameters Estimation – CAPE Model [8] have been developed to minimize the difference between a model and laboratory or well measurements. They could be coupled with our new resistivity acquisition method.

In this work, the Nelder-Mead simplex algorithm described by Lagarias et al. [9] (direct search method) is used to find the minimum of the objective function O. Fig.6 shows the shape of the objective function. An initial guess with a saturation exponent n according to petrophysics will converge to the solution due to absence of local minimums and the quasi-convex behaviour of the function.

In the event of not finding a solution, a meta-heuristic algorithm or hybrid optimization model [10] can be implemented to escape from a "non-convex" part of the function. In the various tests performed, this situation has not been faced.

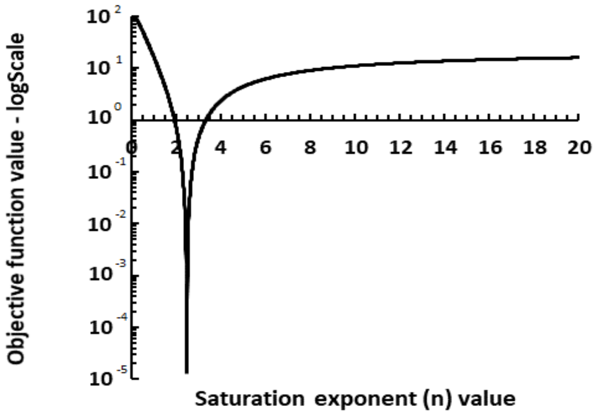

Fig. 6. Objective function shape.

3 Results and Discussion

In order to validate the WiRI method, a two-step approach has been followed. The first step, explained in section 3.1, is a validation of the numerical optimization process. The second one (3.2 – 3.3) presents the results of an entire WiRI measurement process versus a reference method: the PP method. For the PP experiments, most of the advices to maximize data quality from F. Pairoys [11] have been followed.

3.1 WiRI Inversion on UFPCRI Data

Before acquiring WiRI data, the testing of the WiRI inversion is advisable using data coming from the UFPCRI method. Data was acquired on an outcrop sample (25 p.u – 78 mD) in oil water drainage mode.

For the UFPCRI study, Faurissoux *et al.* [5], performed multi-electrode measurements on samples. After each centrifuge step, the sample was removed from the centrifuge for resistivity profile (Keysight E4980A precision LCR meter at 1 V and 1KHz.) and NMR saturation profile measurements.

At each centrifuge speed, the UFPCRI generates a dataset containing:

1. Resistivity profile along the sample
2. Volume produced in the centrifuge
3. NMR saturation profiles

As the WiRI method requires only resistivity profiles and produced volumes at each centrifuge speed, an UFPCRI dataset is used to test the WiRI inversion as first assessment

The first speed of rotation was not correctly chosen (1500 rotation per minutes) and caused more produced volume than desired (i.e. the first data point of Sw is low).

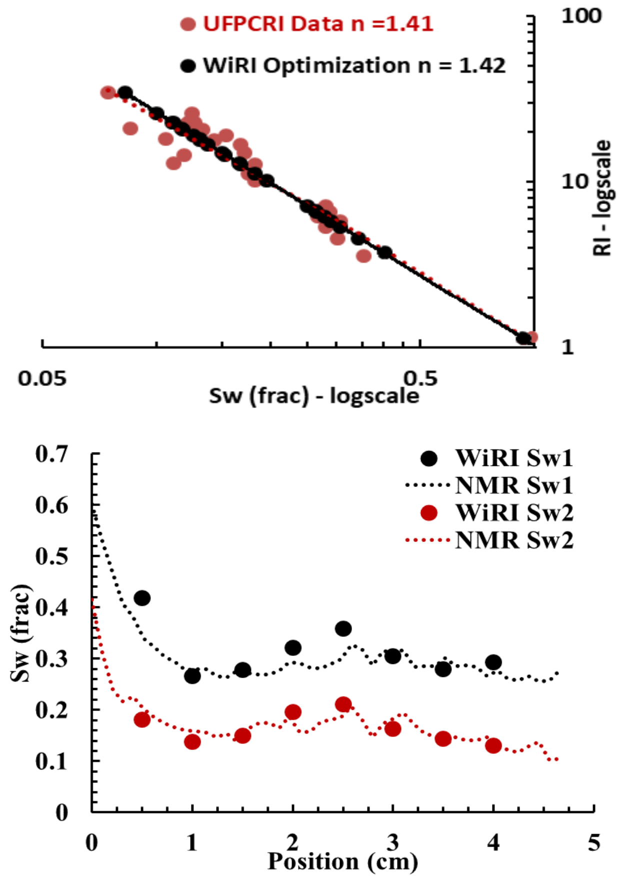

Fig. 7. Comparison between the WiRI and UFPCRI method applied to the same dataset. **a-** RI/Sw logscale graph for determination of exponent n **b-** Saturation profiles NMR versus reconstructed profiles with WiRI inversion.

Fig.7.a shows the saturation exponent determined from UFPCRI versus the saturation exponent from WiRI inversion with same RI and V_{prod}. In this case, the WiRI inversion gives an n exponent close to the UFPCRI. With the WiRI method, a single n value is found to fit the entire dataset. As a result, the RI-Sw log-log curve obtained with WiRI is a straight line

WiRI resistivity profiles can be converted into saturation profiles once the optimum n is found. Fig.7.b presents a comparison between the NMR profiles post UFPCRI and WiRI tests, for two different speeds. WiRI saturation profiles have a lower resolution but enable the non-uniform profiles reconstruction along a sample with good consistency with NMR Imaging.

Therefore, the optimization algorithm is considered as accurate.

3.2 WiRI vs PP

The validation of the entire protocol was done as follows: For the Estaillades outcrop, the conventionnal Porous Plate technique was performed on the sample at ambient conditions in gas water drainage mode. Then, an entire sequence of WiRI was conducted on the same sample (after cleaning, drying and resaturating it with the same brine).
Comparisons between the results obtained with the two methods are shown in Fig.8 and 9. For the WiRI experiment, P_c curve was reconstructed with the method proposed by Green et al. [12] and the S_w calculated from the inversion. The main difference between these two experiments is the time required for obtaining the results: 42 days with PP technique versus 28 hours (including handling) with our new method.
The observations are:

1) IR/S_w log-log curves are very close as well as the n exponent.

2) P_c/S_w shows good consistency (PP was aborted too early due to a failure of the control system).

3) WiRI experiment was quick to set up and the results were interpreted in a short time.

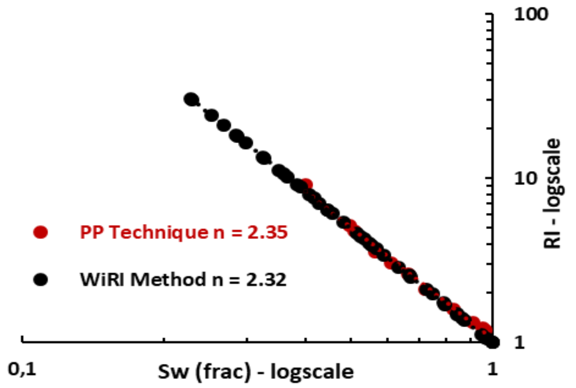

Fig. 8. Resistivity Index Vs Saturation (logscale) comparison between PP experiment and WiRI.

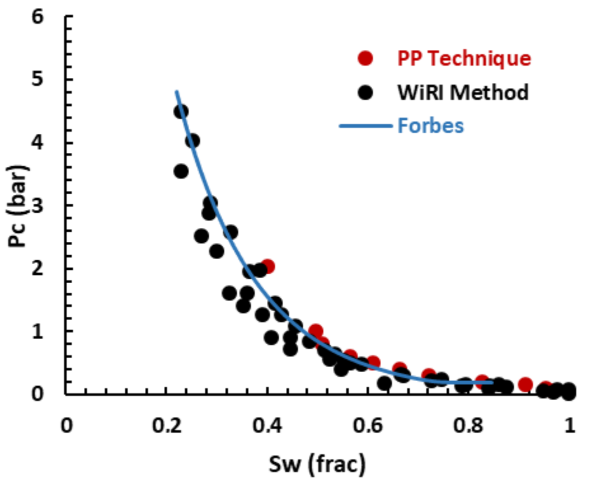

Fig. 9. P_c/S_w curve corresponding to PP technique, WiRI and. Forbes curve from Cydar© simulation with centrifuge data.

3.3 WiRI on real case – Reservoir Core

The WiRI method was applied on twin reservoir sandstone samples, so extracted from the same core and at the same depth. Full core CT scan enabled the selection of an homegeneous zone to extract the samples. Both plugs were cleaned, dryed and saturated with formation water. For the first plug, (38 mm diameter and 25 mm length) the PP technique was performed. For the second plug (30mm diameter and 45 mm length) the complete WiRI sequence was accomplished. The results of the two gas-water drainage experiments are shown in Fig.10 and 11.

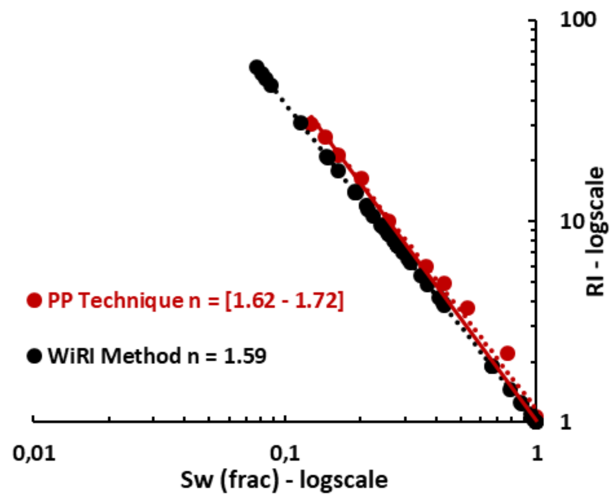

Fig. 10. Resistivity Index vs Saturation (logscale) comparison between PP and WiRI for a reservoir sandstone sample.

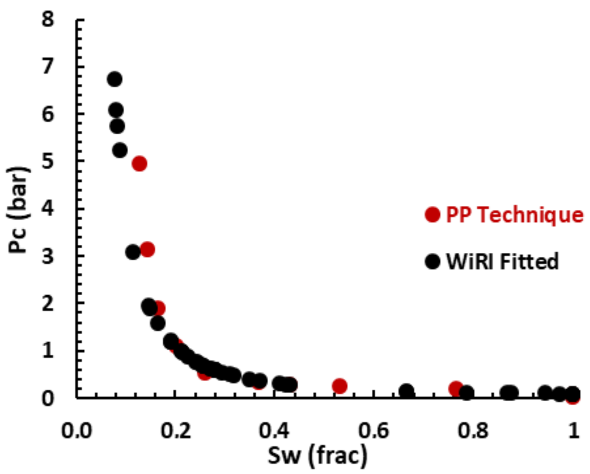

Fig. 11. P_c/S_w curve corresponding to PP technique and WiRI method on reservoir sample.

In Fig.10, the Porous Plate technique gave results subject to interpretation. First, the curvature of RI at high Sw may well be explained by a moving shock front [13]. Second, PP data is subject to measurement uncertainties. Consequently, the n exponent obtained with the PP technique was found to be between 1.62 (red dotted line) and 1.72 (red continuous line). With WiRI, n = 1.59. This new method shows expected results, i.e. a determination of n value close to the reference method with a reduced duration and handling. The coherence with the reference method is extended to the capillary pressure curve.
The total duration of the WiRI experimental cycle was 53 hours, compared to the 118 days of experimental duration for the PP method.

These results demonstrate that WiRI provides resistivity and capillary pressure data in the same timeframe as log interpretation. This new tool is designed to provide a quick and simple measurement and data-set. It can be used in the following ways:

1) Provide quick additional measurements in centrifuge.

2) Use the data acquired to complete a reference method (or to get an idea of the curves trends before starting a long reference method).

3) Automate acquisition, interpretation and Archie's parameter determination.

3.4 Electrode spacing – measurements uncertainties

In a centrifuge, the capillary pressure gradient induces a non-uniform saturation profile along the samples. Unfortunately, resistivity measurements are discrete and do not allow representing this continuous profile. It is then obvious that the higher the resistivity resolution, more correct will be the inversion.

1) Sensitivity to electrode spacing at zero noise

In this section, a WiRI acquisition is simulated for one hundred thousand samples (with different petrophysical characteristics).

Simulations with different S_w profiles, porosities and n exponents have been performed without noise in the produced water volumes and the Rt values. Each simulation contains the WiRI optimization algorithm presented in section 2.4 for different electrode spacing to determine the n exponent. The Mean Absolute Percentage Error (MAPE) between n_a ,the actual fixed n value, and n_f, the forecast value given by the optimization, is evaluated by eq.6 for different electrode spacings. Results are plotted against the electrode spacing on Fig.12. The red point represents the electrode spacing used for our WiRI method.

$$MAPE = 100 * \frac{1}{N_{Sim}} * \sum_{i=1}^{NSim} \left| \frac{n_a - n_f}{n_a} \right| \qquad (6)$$

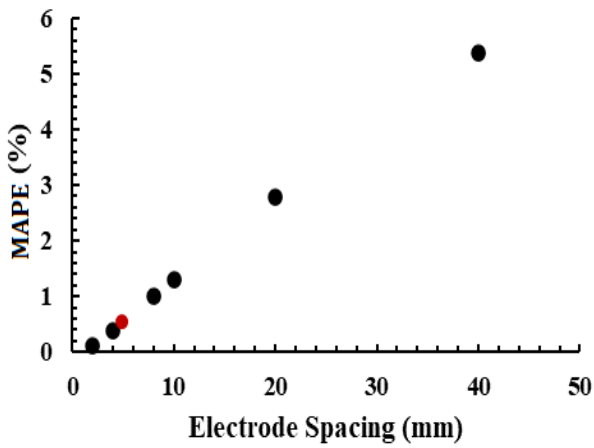

Fig. 12. Impact of the Rt profile resolution on the saturation exponent mean error (evaluation done on 100 000 synthetic profiles). The red point represents the electrode spacing used for our WiRI method.

MAPE decreases linearly with electrode spacing. Below 8 mm spacing, the mean error is less than 1 % of the fixed n value. With our tailor-made technology (detailed in section 2.1), our measurement system ensures that it will nor add a measurement error due to spacing greater than 1%.

2) Noise impact on measurements and inversion

In this section, one hundred thousand WiRI acquisitions are simulated on the same sample.

In order to evaluate the impact of measurement uncertainties, simulations have been performed with the introduction of a ± 5% relative error on R_t and V_W (the measured values in the process). Impact of the electrode spacing, and the number of centrifuge steps are then analysed in Fig.13 with MAPE evaluation and Relative Standard Deviation (RSD or %RSD) defined in eq.7 with $\overline{n_f}$ the mean value of the forecasted n exponents.

$$\%RSD = \frac{100}{\overline{n_f}} * \sqrt{\frac{\sum_{i=1}^{N_{Sim}} \left(n_f - \overline{n_f}\right)^2}{N_{Sim} - 1}} \qquad (7)$$

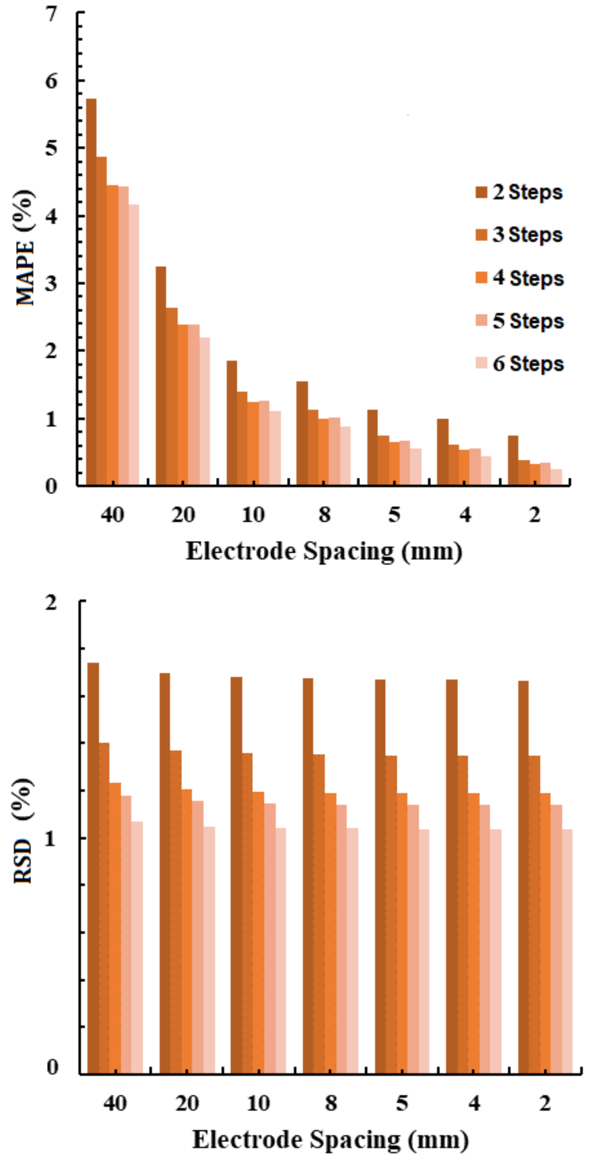

Fig. 13. Impact of centrifuge steps and electrode spacing on optimization process with synthetic data **a-** MAPE (%) evaluation for multiple electrode spacings and multiple speed steps **b-** The corresponding %RSD

As expected, Fig.13. shows that decreasing the electrode spacing improve the MAPE while increasing the number of centrifuge steps improve the %RSD. The lower the electrode spacing the higher the accuracy. The higher the number of centrifuge steps the higher the precision.

Results from this numerical investigation have been considered during our experiments. Electrode spacing is 5 mm and number of centrifuge steps is high enough to minimize standard deviation (between 4 and 6 for each experiment).

3.5 Heterogeneity - Discussion

The WiRI method has two very strong assumptions:

- A uniform porosity profile along the axis of the cylindrical plug

If the sample has heterogeneous pore distribution, it can be early identified qualitatively in the process using NMR, Resistivity profile (R0 profile) at Sw=100% or quantitatively from X-CT [14]. Big differences of R_0 between each slice is a first clue of porosity heterogeneity. In this case, another method will probably be more suitable.

- A uniform Archie n exponent profile along the axis of the cylindrical plug

The presented WiRI process has an objective function for the entire sample, therefore a single value of n is found. However, it is possible to define an objective function for each slice, therefore allowing the determination of n for each slice. Varying values of n in different resistivity slices could give a clue of n exponent heterogeneity. Work is currently ongoing to develop this approach.

Despite the drawbacks above reported, the total duration of WiRI method is so reduced compared to other methods that it is still interesting to finish the process even if heterogeneity is detected. Results could give a first trend or idea of the behaviour of the resistivity with saturation variation, helping the design of more conventional measurements such as PP.

CONCLUSION

The technique presented here is based on wireless transmission of resistivity data during a centrifuge test. For the first time, an experimental method (WiRI) allows the determination of the capillary pressure curve and the saturation exponent n during a multistep centrifuge process. This technique combines the method proposed by Green *et al.* [12] to derive capillary pressure with a novel approach to provide resistivity index wirelessly. WiRI has the advantage of avoiding the porous plate drawbacks (loss of capillary contact, long equilibrium time, risk of leaks) and avoiding extensive handling and interpretation time by the use of numerical optimization.

Numerous simulations have been done to determine and ensure the best experimental conditions for this technique. The obtained results showed good consistency for both outcrops and reservoir core with a satisfying n value determination and P_c curve.

To summarize, the proposed method:

- Simplifies the acquisition and the processing of RI measurements with wireless technology and optimization method.

- Allows the acquisition of additional measurements during centrifuge.
- Is able to deliver fast measurements and interpretation of the PCRI data.

Further work is ongoing to:

- Allow high pressure and temperature experiments.
- Adapt the system for different sample scales.
- Improve the detection and the treatment of heterogeneities during the centrifugation.

ACKNOWLEDGEMENTS

The authors thank Rachel Jorand, Fabrice Pairoys, Regis Brugidou, Ghislain Pujol, Ata Nepesov, Laurent Rochereau and Victor De Oliveira Fernandes for fruitful discussions and technical assistance.

REFERENCES

[1] Archie, G.E. "The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics." Trans 146: 54–62, (1942)

[2] M. Fleury, "FRIM: A Fast Resistivity Index Measurement Method," in SCA, paper 29, (1998)

[3] M. Fleury, “Advances in resistivity measurements using the FRIM method at reservoir conditions. Application to carbonates” in SCA, paper 31, (2003)

[4] N. Bona, E. Rossi and B. Bam, "Ultrafast Determination of Archie and Indonesia m&n Exponents for Electric log Interpretation: a Tight Gas Example," IPTC-17446-MS, (2014)

[5] P. Faurissoux, A. Colombain, G. Pujol, O. Fraute, B. Nicot, “Ultra Fast Capillary Pressure and Resistivity Index measurements (UFPCRI) combining Centrifugation, NMR Imaging, and resistivity Profiling” in SCA, paper 2, (2017)

[6] A. Garrouch and M. Sharma, "Techniques for the Measurement of Electrical Properties of Cores in the Frequency Range 10Hz to 10MHz," in SCA, paper 11, (1992)

[7] C. Durand, R. Lenormand, “Resistivity measurements while centrifuging” in SCA, paper 15, (1997)

[8] R.E. Maute, SPE, W.D. Lyle, SPE, and Eve S. Sprunt, SPE, Mobil R&D Corp, “Improved Data-Analysis Method Determines Archie Parameters from Core Data”, in SPE-19399-PA, (1992)

[9] Lagarias, J. C., J. A. Reeds, M. H. Wright, and P. E. Wright, “Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions”, in SIAM Journal of Optimization, Vol. 9, Number 1, pp. 112–147, (1998)

[10] Jianjun Liu, Honglei Xu, Guoning Wu, and Kok Lay Teo, “A New Hybrid Optimization Algorithm for the Estimation of Archie Parameters”, in book - Optimization Methods, Theory and Application pp 137-154 Chapter 7, (1998)

[11] F. Pairoys, “Rock Electrical Properties from Porous Plate and Resistivity Experiments: Tips to Maximize Data Quality”, in SCA, paper 38, (2018)

[12] D. Green, J. Dick, J. Gardner, B. Balcom and B. Zhou, "Comparison Study of Capillary Pressure Curves Obtained Using Traditional Centrifuge and Magnetic Resonance Imaging Techniques," in SCA, paper 30, (2007)

[13] Jos G. Maas, Niko van der Post, Krijn H. van der Gyp, John G.C. Coenen and Wim J. Looyestijn, “Resistivity Index Measurements Under Weak Capillary Forces”, in SCA, paper18, (2000)

[14] J. G. Maas, N. Springer, A. Hebing, “Defining a sample heterogeneity cut-off value to obtain representative Special Core analysis (SCAL) measurements, in SCA, paper 24, (2019)