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# New Experimental Approach of Saturation Exponent Measurements by Continuous Injection Technique

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# طريقة معمليّة جديدة لتحديد معامل التشبّع المائي بأسلوب الحقن المستمر

عمران المحتوت، و. ي. ميسن و محمد نصر

إن تحديد التشبع المائي في الصخور بواسطة معدات سرود المقاومة السلكية يعتمد أساساً على قيمة معامل المقاومة والذي يتم قياسه معملياً لنماذج العينات الصخرية باستخدام العلاقة المعروفة باسم (Archie) وهي ($I_R=R/R_0=Sw^n$).

إن الأخطاء المحتملة في إيجاد معامل التشبع (n) يؤدي بلا شك إلى حدوث أخطاء جدية في تقدير التشبعات الهيدروكربونية في الصخور.. تعتبر طريقة الحقن المستمر من الطرق المعملية الشائعة في الصناعة النفطية لإيجاد معامل التشبع وذلك بحقن أحد الأطوار (الماء المالح) لإزاحة الطور الأخير (الزيت) عند معدل حقن ثابت.

في هذه الدراسة تم التحقق من استخدام أسلوب معملي جديد لإيجاد معامل التشبع المائي لعدد من نماذج الصخور بطريقة الحقن المستمر تحت معدلات حقن متغيرة. كما تم اختيار أربعة نماذج صخرية جيرية ذات خواص بتروفيزيائية مختلفة في النفاذية والمسامية لدراسة تأثير معدلات الحقن المتغيرة على قيم معامل التشبع، وشكل العلاقة بين معامل المقاومة والتشبع المائي في الصخور، وتبين بشكل واضح أن استخدام أسلوب الحقن المستمر بمعدلات متعددة وخاصة في الصخور ذات التبلل المائي (Water wet) ولمدى واسع من قيم التشبع المائي يضمن الحصول على علاقة منتظمة لمعامل التشبع المائي وخاصة عند الحقن بمعدلات منخفضة. وبذلك يمكن الاستنتاج أن معدل الحقن له دور مهم في تحديد شكل العلاقة التي تربط معامل المقاومة الصخرية ($I_R$) مع التشبع المائي ($S_W$) والذي سيؤدي بلا شك للتوصل إلى قيمة مناسبة ودقيقة لمعامل التشبع المائي (n) والذي بالإمكان استخدامه بثقة عالية في حسابات التشبع الهيدروكربوني بطريقة السرود الكهربائية.

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**Abstract** *Water saturation determination from wireline resistivity log depends on the measurements of resistivity index on core samples. Resistivity index measurements are carried out in laboratory using Archie's equation;* $I_R = R_t/R_0 = S_W^{-n}$. *Errors in the saturation exponent n, can give rise to serious errors in the estimation of hydrocarbon saturations. One of the major sources of uncertainty is the method of measurements. The continuous injection technique is used routinely in the oil industry. In this technique one fluid phase (brine) is continuously displaced by another phase (oil) at a constant injection rate. In this paper, a new experimental approach is proposed in which repeated resistivity index measurements are carried out on the same samples at various injection rates. The effect of injection rate on saturation exponent for core samples can be investigated. Four carbonate core samples with a wide range of porosity and permeability were tested to demonstrate resistivity index measurements at low and high injection rates. Use of continuous injection technique at different rates has illustrated that for the water-wet samples a uniform* $I_R/S_W$ *correlation was established over wide range of* $S_W$ *when low rate is used. It is concluded that the injection rate selection has an important role on the* $I_R/S_W$ *relation.*

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*It is recommended as a result of this work that for resistivity index measurements, various injection rates should be used to obtain the best $I_R/S_W$ relation and consequently the proper saturation exponent could be obtained.*

## INTRODUCTION

Water saturation is commonly determined from electric well logs based on an empirical Archie's equation [1]; $I_R = S_W^{-n} = R_t/R_0$. The Archie's parameters are frequently obtained from laboratory measurements on core samples. An assumption in laboratory measurements is that the sample saturation is distributed uniformly. It is assumed also that saturation exponent $n$, is constant over $S_W$ range. Many cases are being encountered where resistivity index ($I_R$) versus brine saturation ($S_W$) gives non-linear relationship. Wettability, micro-porosity, capillary end effects, and some other factors which cause this non-linearity.

The experimental procedure design, and especially selection of injection rate in continuous injection technique could have an important influence on the non-linearity of $I_R/S_W$ curves. The inaccurate evaluation of saturation exponent can result in large errors in hydrocarbon calculation as described by de Waal [2]. In order to use Archie's equation, the uniform water distribution should be maintained along the core sample, and $I_R/S_W$ should have a linear relation (i.e. constant $n$). If improper desaturation procedure is used in resistivity index measurements, a non-uniform saturation distribution may prevail and invalid $I_R/S_W$ curves will be produced, and hence erroneous value of saturation exponent may be obtained. The influence of injection rate on $I_R/S_W$ relationships has received much less attention in the past, probably on account of the time and cost involved in such experiments. Generally, the fluid distribution in porous media is function of rock pore structure characteristics, wettability, fluid properties, stresses, and experimental conditions, rate of injection of displacing fluid, desaturation history. The pore structure also affects the shape of displacing front which in turn modifies the fluid distribution behind it and hence the resistivity values [3].

## SATURATION EXPONENT TECHNIQUES

Numerous number of techniques have been devised to measure the electrical resistivity of rocks partially saturated with brine. Porous plate method, and continuous injection technique are the recent techniques used in the oil industry with wider use of the continuous technique. Lyle and Mills [4] showed theoretically that the laboratory-derived Archie saturation exponent may be different from the actual value, and concluded that whenever the core is other than uniformly saturated, the $I_R$ versus $S_W$ log-log plot will exhibit curvature. However, the most recent developed technique to measure the resistivity index is continuous injection which believed to be powerful, accurate and rapid, as well as it provides continuous $I_R/S_W$ curve rather than a limited number of points [2]. It is reliable where experimental error can be minimized by automation of measurements procedure and performed at an equivalent reservoir stress. In this technique oil is injected at a constant rate to displace brine. The porous plate method has been used to obtain uniform desaturation and uniform $I_R/S_W$ relation as described by Maerefat *et al.* [5]. They concluded that sufficient desaturation time should be allowed to obtain homogeneous saturation. It is believed that at capillary and electrical equilibrium, the uniform saturation distribution can be achieved, but small scale permeability heterogeneity seems to cause non-linearity even after this equilibrium [6]. Lewis *et al.* [7], used low injection rate to minimize fingering which may occurred during high injection process, then they used simultaneously high rate to compress the length of capillary end effect. They recommended that four-electrodes system which is not affected by contact resistance to be used. In their experiments they tested high porosity and permeability samples, and concluded that the capillary end effect and viscous fingering cause the non-linearity of $I_R/S_W$ relationship [7]. Spurt [8] used X-ray CT scan to monitor saturation distribution along the core samples. He changed capillary pressure (not injection rate) and encountered problem in achieving homogenous saturation during resistivity index tests for the two high porosity and permeability grainstone samples desaturated at constant oil/brine capillary pressure. Gray *et al.*, [9] measured $I_R$ for sandstone samples at low constant injection rate (0.02 cc/hr), they selected this rate so that an insignificant pressure drop existed across the sample through the desaturation processes. However, the uniform $I_R/S_W$ plot had not been achieved except for $S_W$ less than 45%. Elashahab *et al.*, [10] used multiple potential electrodes system in $I_R$ measurement to enable assessment of saturation distribution and end effect.

The injection rate chosen for $I_R$ measurements by continuous injection technique, theoretically should be

(1) not so high, as to introduce fingering or channeling through the core sample,

(2) low to prevent significant saturation change at a given time along the sample.

This criteria was applied in this investigation. Four carbonate samples, 1.5" diameter, 3" length with wide range of porosity and permeability were collected to study the effect of injection rate on $I_R/S_W$ relationship. The samples properties are listed in Table 1.

**Table 1. The physical properties of the samples**

| *Sample No.* | *ϕ (%)* | *k (mD)* | *G.D. (gm/cc)* |
|---|---|---|---|
| 1 | 15.1 | 3.74 | 2.859 |
| 2 | 34.5 | 29.09 | 2.853 |
| 3 | 33.0 | 26.14 | 2.834 |
| 4 | 17.7 | 9.5 | 2.850 |

Repeated resistivity index measurements by continuous injection technique on these samples were performed at alternating injection rate.

## EXPERIMENTAL PROCEDURE

Low and high oil injection rate experiments were carried out on these samples and the rates chosen were (0.03 and 0.15) cc/hr. Fig. 1 shows the apparatus of $I_R$ measurements and Fig. 2 illustrate the core sleeve with multiple elcetrodes system. The fully brine-saturated samples were mounted in a multiple core holder made of aluminum and subjected to confining pressure of 400 psi, which was increased to 3000 psi. The sample pore volume was calculated based on the brine volume collected in pipettes which is attached to the outlet of each sample after the system was being maintained in equilibrium. Oil was injected at one end of the samples, brine (100 g/l, NaCl) was expelled at the other ends, through a semi-permeable membrane. The semi-permeable membrane was supported on a brine saturated high porosity glass disc. Both voltage, phase angle and temperature were monitored continuously during the oil injection process. All samples were made preferentially water-wet, and firstly cleaned with methanol, then fired to 600°C for one day in a high temperature furnace to make them water-wet [11].

Before the desaturation processes began, and samples loaded, the resistivity of fully saturated samples ($R_0$) was measured. The samples loaded to the core holder, then oil/brine desaturation process started and $I_R$ measured when capillary and electrical equilibrium were reached. This equilibrium was indicated when there was no further change in resistance (i.e. no further fluid redistributed along the core length). Two different rates of 0.03 cc/hr and 0.15 cc/hr were used for the displacement of brine

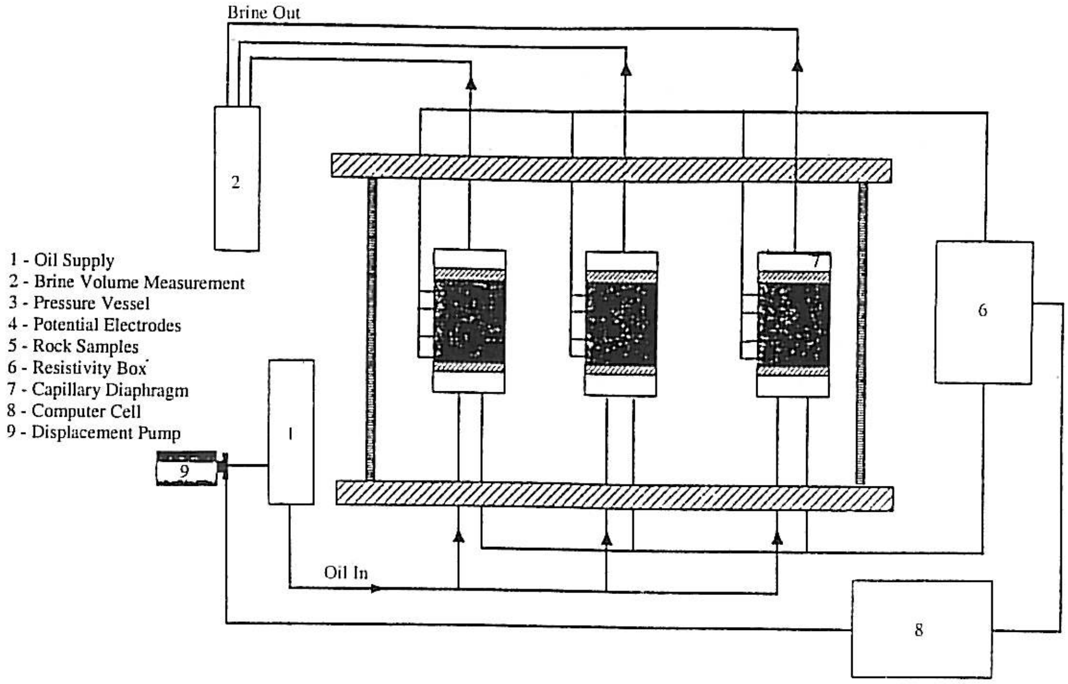


Fig. 1. Schematic diagram of core holder and resistivity index measurement apparatus

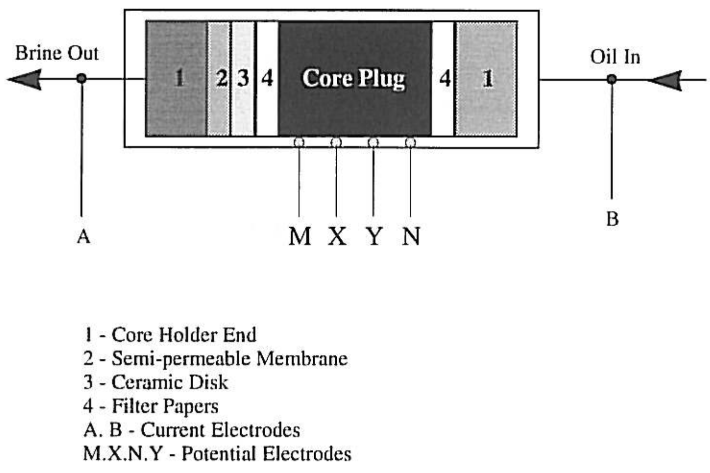


Fig. 2. Schematic diagram of core sleeve with multi electrodes system

water by oil from the core samples. The amount of displaced fluid was measured by a calibrated potentiometer connected to the pump piston. The pump is regularly calibrated at experiments conditions. The samples were subjected to re-cleaning process to remove oil contamination and the cleaning method used kept them in water-wet condition and remain as that throughout the experiment. The resistance of samples measured at 1 kHz, to avoid polarization effect [11]. Resistivity was corrected to slight temperature variations by using Arp's equation [12].

On the second part of this experimental investigation, the resistivity index measurements were carried out using porous plate method, in order to compare it with continuous injection technique results. In this method the resistivity measurements and desaturation process take place separately. The samples were desaturated simultaneously by placing them on a porous plate in pressure cell, and gas pressure was applied. The gas (nitrogen) enters the samples from all directions except from end face. The gas pressure was maintained until no more brine produced. After the capillary equilibrium (samples held 4–5 days in plate) at each pressure point is reached, the gas is then released, and the samples removed from the pressure cell and weight measurements were taken as well as resistivity readings. The procedure was repeated by increasing gas pressure at various desaturation points.

## RESULTS AND DISCUSSION

The continuous injection technique results in an accurate and precise determination of $I_R$ versus $S_W$ relationship of core samples [2]. The advantage of this technique is providing a continuous $I_R/S_W$ curve rather than, a limited number of data points, this is of particular importance in the case of curved $I_R/S_W$ relationship. In this technique, the non-wetting phase (oil) is injected into the sample at a constant rate. A uniform saturation distribution along the length of core sample is required to measure saturation exponent accurately which leads to proper hydrocarbon evaluation. It is believed that by using this technique with very low injection rate might achieve the homogenous saturation distribution and uniform $I_R/S_W$ relation may be obtained.

To begin the continuous injection process, the displacement pump starts to inject the oil core holder. Initially this was performed at low rate (0.03 cc/hr) for displacing brine from the flowlines. This low rate has been selected such that an amount of oil corresponding to samples 1, 2, 3 and 4 pore volumes will be injected approximately in (26, 25, 13 and 12) days respectively, and for high rate (0.15 cc/hr) the samples pore volumes will be injected at (8, 8, 4 and 4) days respectively. The continuous injection of oil was stopped for each sample individually after that given time or when no more brine expelled from the sample. The samples then were cleaned and resaturated. After several resistivity readings were taken, $S_W$ was determined. Figures 3, 4, 5 and 6 show the measured resistivity index versus average brine saturation for all the samples at low and high rates. The Archie's relation of $I_R = S_W^{-n}$ assumes that a straight-line relationship of log ($I_R$) versus log ($S_W$) exists (a constant saturation exponent over the entire saturation range). This assumption has been considered by many previous investigators [13, 14, 15, 16] as "invalid". In this experimental investigation this assumption may be proven as "valid".

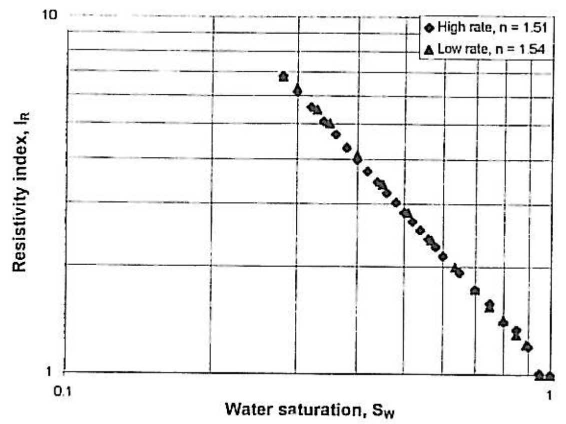


Fig. 3. Resistivity index, $I_R$ vs. water saturation, $S_W$ for core sample No. 1 at low and high injection rate

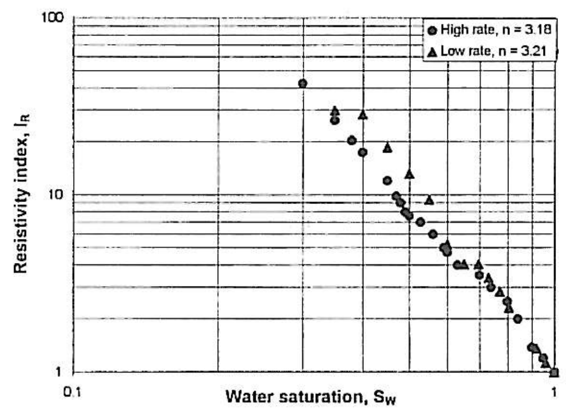


Fig. 4. Resistivity index, $I_R$ vs. water saturation, $S_W$ for core sample No 2 at low and high injection rate

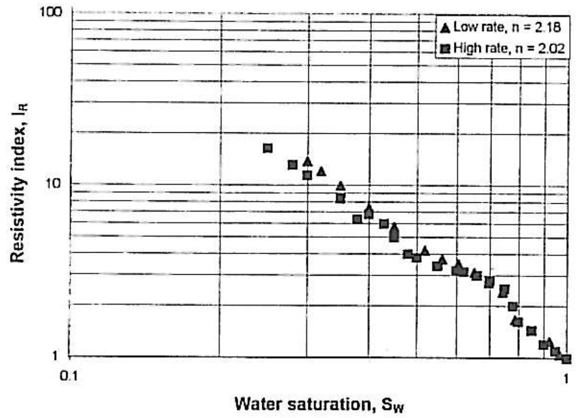


Fig. 5. Resistivity index, $I_R$ vs. water saturation, $S_W$ for core sample No. 3 at low and high injection rate

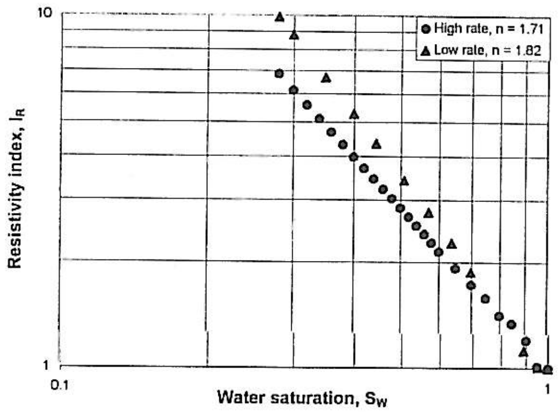


Fig. 6. Resistivity index, $I_R$ vs. water saturation, $S_W$ for core sample No 4 at low and high injection rate

However by comparing the plots of $I_R/S_W$ for these tested samples with each other and with porous plate measurements, it has been found that a straight $I_R/S_W$ correlation can be established over much wider range of $S_W$ as shown in Figs. 3, 4, 5 and 6.

Basically, when non-wetting phase injected into the samples to displace wetting phase, the large pores will be penetrated firstly because they represent less resistance. As desaturation progresses a saturation heterogeneity through the core sample may persists and yield nonlinearity of $I_R/S_W$, but this may depends on the non-wetting injection rate and the heterogeneity of the core samples themselves. A rate of 0.03 cc/hr in sample 3 (Fig. 5), can be considered as the optimum because linear $I_R/S_W$ relation was obtained. Also for sample 2 (Fig. 4), a constant $n$ obtained over a good range of $S_W$ by using the same injection rate. In contrast the $I_R/S_W$ relationship becomes linear at brine saturation below (65–75%) when a low rate is chosen, as it is shown in Figs. 3, 4, 5 and 6. In this wide range of $S_W$,

**Table 2. Saturation exponent values by two techniques**

| | *Continuous Injection Technique* | | *Porous Plate Method* |
|---|---|---|---|
| *Sample No.* | *Low Rate* | *High Rate* | |
| 1 | 1.54 | 1.51 | 1.55 |
| 2 | 2.18 | 2.02 | 2.15 |
| 3 | 3.21 | 3.18 | 3.18 |
| 4 | 1.82 | 1.71 | 1.83 |

the Archie's assumption has been proven its validity, and $n$ from linear part of $I_R/S_W$ curves should be used, provided that the desaturation process should be achieved at least to the reservoir $S_W$ level in laboratory, to avoid improper extrapolation. On the other hand, high injection rate can create significant pressure drop through the desaturation process which results in an invalid $I_R/S_W$ relations. Although the carbonate samples tested here have bimodal pore size distribution which believed to be the main cause of the non-linearity of $I_R/S_W$, the selection of injection rate has an important role to overcome this problem. Also another interesting feature was observed, that low permeability sample (sample 1) shows clear linear $I_R/S_W$ relation at $S_W$ below 75%, (Fig. 3). In sample 3 (Fig. 5), the resistivity measurements for $S_W > 65$ and $< 100\%$ are useless in determining $n$, when low rate is used, but this range of $S_W$ is much less when a high rate is used The saturation exponent values were found to be 1.55, 2.15, 3.18 and 1.83 by using the porous plate method. Very interesting feature was found where these $n$ values are close to those measured by continuous injection technique at low rates. Again this confirms the importance of injection rate for establishment of proper $I_R/S_W$ correlations. Table (2) presents the $n$ values by the two methods.

## CONCLUSIONS

Performing resistivity index by continuous injection technique at a fixed-rate may produce inaccurate ($n$) values, and subsequently an error in $S_W$ determinations. The influence of injection rate on the resistivity index/brine saturation relationship has an important role to be considered. These measurements should be repeated at various injection rates to select an optimum rate for each core sample (proper $n$ value).

This has shown that the low injection rate method is prefered on the high rate method, due to insignificant saturation changes taking place through the core sample at a given time. Furthermore, the low rate would produce linear relationship of $I_R$ versus $S_W$ over much wider range of $S_W$. This new experimental approach has illustrated that for water-wet samples a uniform $I_R/S_W$ relation can be established. Therefore the usage of larger number of homogeneous and heterogeneous samples with various injection rates (high, moderate and low) is required for further investigation.

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