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Effect of Viscosity Ratio on Archie Saturation Exponent

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تأثير نسبة اللزوجة على مُعامل التشبع المائي للصخور

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إن قياس معامل التشبع المائي للصخور بواسطة تسجيلات مقاومة التيار الكهربائي يعتمد على قياس معامل المقاومة الكهربائية والذي يحدد معملياً على عينات لبية باستخدام معادلة Archie.

أي خطأ في قياسات معامل التشبع المائي سوف ينتج عنه خطأ كبير في تقديم الاحتياطي النفطي في المكامن النفطية. معادلة Archie تفترض أن معامل التشبع المائي يتغير تبعاً لتغير معامل مقاومة التيار الكهربائي في الصخور ولا تأخذ في الاعتبار تغيير الخواص الطبيعية لسوائل المكامن النفطية.

إزداد في الأونة الأخيرة إستعمال طريقة الحقن المستمر في الصناعة النفطية حيث يتم وبصفة مستمرة إحلال المياه المالحة محل النفط الخام تحت نسبة لزوجة ثابتة. في هذه الدراسة تم تقديم طريقة معملية لقياس معامل مقاومة التيار الكهربائي في الصخور باستخدام عدة نسب للزوجة سوائل الإزاحة والسوائل المكمنية المزاحة، حيث أن جميع الطرق القديمة تستخدم نسبة لزوجة ثابتة. كما تم دراسة تأثير تغيير نسب اللزوجة على تغيير معامل التشبع المائي في المكامن النفطية.

تم إجراء التجارب المعملية على عدد أربع عينات صخرية ذات نسب لزوجة عالية ومنخفضة. أثبتت نتائج هذه التجارب أن تغيير نسبة اللزوجة أثّر تأثيراً كبيراً على شكل تنمى العلاقة بين معامل التشبع المائي ومعامل مقاومة التيار الكهربائي في الصخور، حيث يمكن ملاحظة ذلك في المنحنيات المتضمنة لهذه الدراسة، كما لوحظ أن خواص السوائل المكمنية وكذلك سوائل الإزاحة مهمة جداً عند إجراء التجارب المعملية لحساب معامل التشبع المائي للصخور، وتعتبر لزوجة هذه السوائل من أهم هذه الصفات.

Abstract: *Water saturation determination from wireline resistivity log data depends on measurement of the resistivity index on core samples. Resistivity index measurements carried out in the laboratory are the input to the second Archie equation; $I=Rt.Ro\text{-}Sw^{-n}$. Errors in the evaluation of the saturation exponent (n) can give rise to serious errors in the estimation of hydrocarbon saturations. This equation assumes that the same value of water saturation should give the same value of resistivity whatever the fluids characteristics used, because Sw and Rt are the only variables in the equation. It is assumed that this equation is independent of the fluids characteristics.*

The continuous injection technique is used increasingly in the oil industry. In this technique, one fluid phase (brine) is continuously displaced by another (oil) at a fixed viscosity (Brine/Oil) ratio. An experimental approach is proposed here in which repeated resistivity index measurements are carried out on the same core samples at different viscosity ratios. The effect of viscosity ratio on the saturation exponent for the core sample can then be investigated. Four carbonate samples with a wide range of porosity and permeability were tested to demonstrate resistivity index measurements at low and high viscosity ratios. The results showed that the fluid characteristics, such as viscosity ratio, have a crucial effect on the I versus Sw relationship. For some of the viscosity ratio used, the second Archie

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equation consists of two straight-line segments on a log-log; this may be due to a bimodal pore size distribution in the core samples used or due to the influence of other factors. Use of the continuous injection technique at different viscosity ratios has demonstrated that for water-wet samples, a different I versus Sw correlation can be obtained. It is, therefore, recommended that for resistivity index measurements, fluids characteristics represent the reservoir of interset should be used in order to obtain a reliable I versus Sw relation and, hence, an appropriate value of saturation exponent.

INTRODUCTION

Water saturation is commonly determined from electric well logs based on the second Archie equation[1]: $I=Sw^{-n}=Rt/Ro$. The Archie's parameters are usually obtained from laboratory measurements on core samples. It is assumed in laboratory measurements, that the saturation is distributed uniformly throughout the sample and that the saturation exponent n is constant over the saturation range. However, many cases are encountered where the resistivity index (I) shows a non-linear relationship with the brine saturation (Sw). Wettability, microporosity and capillary end effects are the main factors which contribute to this nonlinearity.

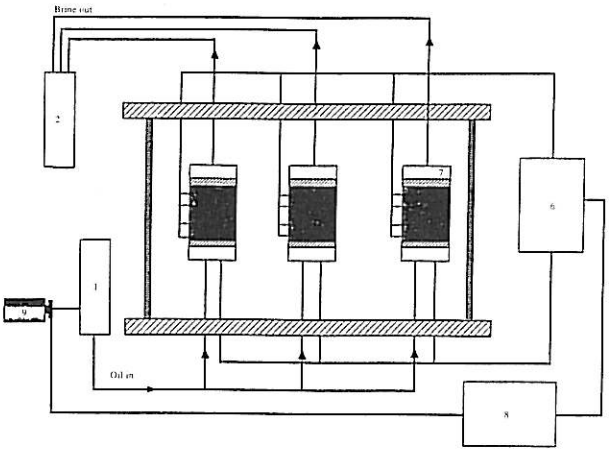
Archie's equation assumes that the same value of water saturation should give the same value of resistivity, whatever the fluid characteristics used, because Sw and Rt are the only variable in the equation. It is also assumed that this equation is independent of the fluids characteristics. The experimental conditions, and especially the viscosity ratio for the continuous injection technique, have an important influence on the I versus Sw curves. If inappropriate oil and brine viscosities are used in resistivity index measurements, an erroneous value of saturation exponent may be obtained. The influence of viscosity ratio on I versus Sw relationships has received little attention in the past, probably because of the time and cost involved in such experiments. However, unreliable values of saturation exponent can result in large errors in hydrocarbon determination[2]. Generally, the fluid distribution in porous media is function of rock type, pore structure characteristics, wettability, fluid properties, stress, rate of injection of displacing fluid and desaturation history. The pore structure also effects the profile of the displacing fluid front which, in turn, modifies the fluid distribution behind it and, hence, the resistivity values[3].

A number of different techniques have been devised to measure the electrical resistivity of rocks partially saturated with brine. The porous plate method, the centrifuge method and the continuous injection method are the techniques currently used in the oil industry. Of these, the most recently developed is the continuous injection method which is powerful, accurate, rapid and provides a continuous curve of I versus Sw rather than a limited number of points[2]. In this technique, oil is injected in order to displace brine at a fixed viscosity ratio. This method has the advantage that experimental error can be minimized by automation of the measurement procedure and measurements can be performed at effective reservoir stress. In this paper, an experimental approach is proposed in which repeated resistivity index measurements are carried out on the same samples at different viscosity ratios.

EXPERIMENTAL PROCEDURE

Low and high viscosity ratio experiments were carried out on selected carbonate samples and the viscosity ratio chosen were respectively 0.1 and 0.6. Figure 1 shows the layout of the apparatus used and Figure 2 illustrates the viton core sleeve with multiple electrode system. The samples, fully saturated with brine of concentration 100 g/l, were then mounted in a multiple core holder made of aluminum and subjected to an initial confining pressure of 400 psi, which was subsequently increased to 3000 psi. The sample pore volume was calculated based on the brine volume collected in pipettes attached to the outlet of each sample. The system was allowed to come to equilibrium and oil was then injected at one end of the sample and brine was expelled at the other end through a semipermeable membrane used to prevent passage of the oil at the outlet of the sample. The semipermeable membrane was supported on a brine saturated high porosity glass disc. Voltage, phase angle and temperature were monitored continuously during the oil injection process. All samples were previously made preferentially water-wet by first cleaning with methanol, then firing to 600°C for one day in a high temperature furnace[4]. Before the desaturation process began and the samples loaded, the resistivity of fully

saturated samples (Ro) were measured. The oil/ brine desaturation process was then started and *I* was measured when both capillary and electrical equilibrium was reached at the confining stress used. This equilibrium was indicated when there was no further change in resistance (*i.e.* no further fluid redistribution along the core length).

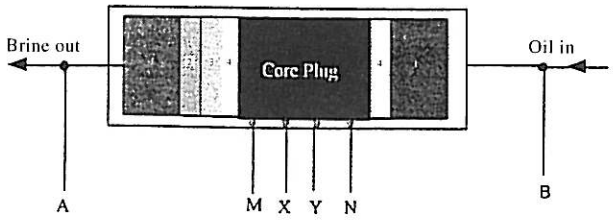


1 – Oil supply
2 – Brine volume measurement
3 – Pressure vessel
4 – Potential electrodes
5 – Rock samples
6 – Resistivity box
7 – Capillary diaphragm
8 – Computer cell
9 – Displacement pump

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

The average core saturation was calculated volumetrically be deducting the volume of brine displaced from the pore volume. Oil was injected at the low rate. A displacement pump equipped with a piston was connected to the core holder. The amount of displaced fluid was measured by a calibrated potentiometer connected to the pump piston. The pump was regularly calibrated for the experimental conditions. The samples were subjected to the re-cleaning process to remove oil contamination and to keep them in water-wet condition throughout the experiment. The resistance of the samples was measured at 1kHz to minimize polarization effects[5]. The resistivity values were corrected for slight temperature variations by using Arp's equation[6].

To begin the continuous injection process, the displacement pump was started to inject the oil into the core holder. The first three samples, saturated with brine (μo = 2 cp) desaturation process was started, and the resistivity index *I* was



1 – Core holder end
2 – Semi-permeable membrane
3 – Ceramic disk
4 – Filter papers
A.B. – Current electrodes
M.X.N.Y. – Potential electrodes

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

measured when the capillary and electrical equilibrium was reached. This equilibrium was indicated when there was no further change in resistivity. The average core saturation was calculated volumetrically by deducting the volume of brine displaced from the pore volume. After, the resistivity index measurements were accomplished for the three samples at a low viscosity ratio. The samples were then unloaded and subjected to recleaning and then reloaded for the next measurements at a high viscosity ration (μw=1.2 cp and μo=2 cp).

DISCUSSION

The viscosity ration (μ_R), defined here as a ratio of displaced (Brine) fluid viscosity to the displacing fluid (oil) viscosity. High (μ_R=0.1) ratio was used. The fluid flows through a porous media (core or reservoir) is affected by the interaction of the local pore structure with viscous, capillary and gravitational forces[7]. The displacement of water by oil in a porous media is not a simple process and does depend on many factors such as the physical properties of the fluids. The flow mechanism, during the displacement, affects the fluids distribution and influences the resistivity index value. A transition zone exists since first oil starts to displace brine and this zone travels along the core sample until the end. The zone has different shapes depending on the pore structure and the forces controlling it. Whenever this transition zone passes through and has a short length while it progresses, the front can be named as flat front, and small clusters will be left behind. When this zone has a longer length, it can be considered as a fingering front. The second type

of front usually leaves larger clusters behind it than the first type. These large clusters would cause non-uniform saturation distribution and curved *I* versus Sw relationship would be obtained. The viscous force is one of many factors which controls and forms the shape of the front and, subsequently, different *I* versus Sw relationships are obtained at different viscosity ratios. Figures 3, 4 and 5 represent *I*/Sw plots for all the tested samples at two viscosity ratios. At a lower ratio, the *I* versus Sw relation is more uniform than at the higher ratio. Also, the desaturation process at low μ_R covers much Sw range than at a high ratio. This can be attributed to the fact that a thin water film is left behind when lower μ_R is used, while a thicker film of water is left behind at a higeher ratio. However, water was produced in case of high μ_R even after oil reached the sample end. It can be considered that a uniform saturation distribution was obtained for the sample at low μ_R. The high viscosity ratio experiments produced n values lower than those at a low ratio and the difference in n values reached about 0.7 and, subsequently, yielded a 12% error in Sw value.

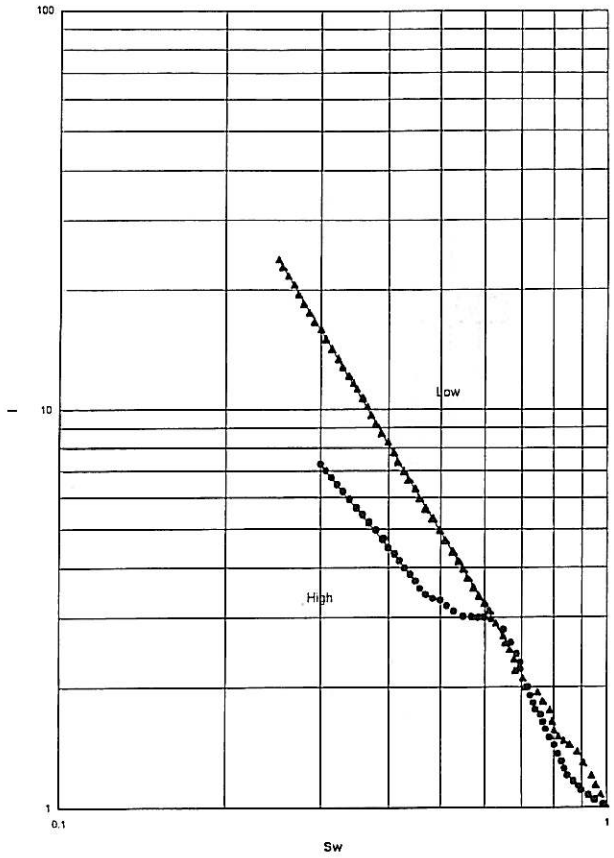


Fig. 4. I *vs* Sw for sample 2 at low and high viscosity ratio.

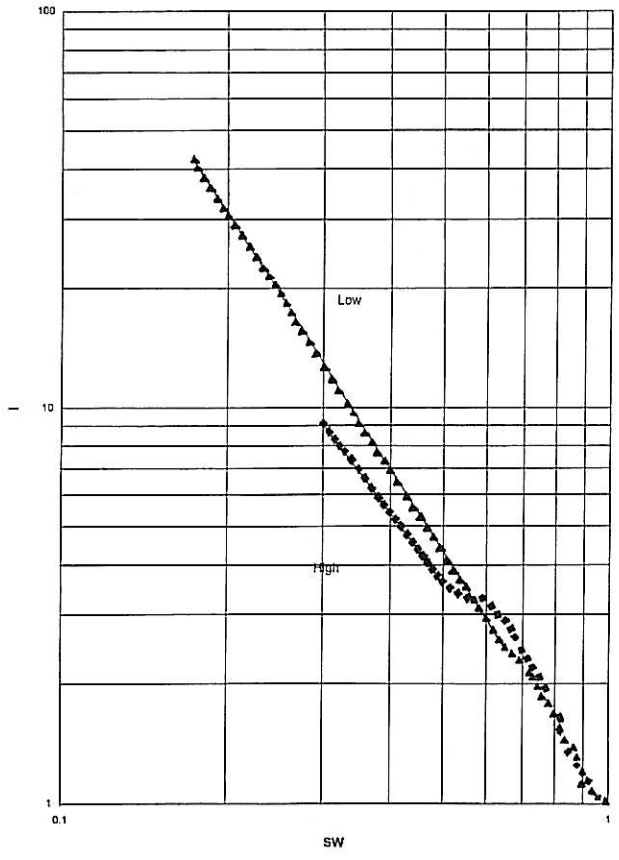


Fig. 3. I *vs* Sw for sample 1 at low and high viscosity ratio.

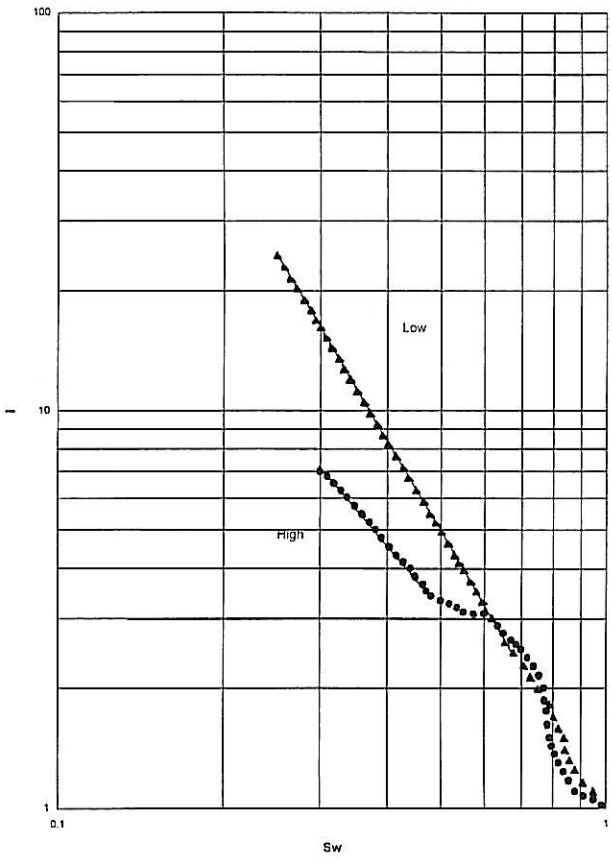


Fig. 5. I *vs* Sw for sample 3 at low and high viscosity ratio.

These high differences confirm the necessity to perform resistivity index measurements with fluid that have the same characteristics as the fluids of the reservoir or the formation under investigation.

CONCLUSIONS

The influence of viscosity ratio on the resistivity index versus brine saturation relation has important consequences for saturation exponent determination by the continuous injection technique. The results obtained above show that measurements of the resistivity index by the continuous injection technique using a fixed viscosity ratio may give an unrepresentative value of n, and lead to error in Sw determination. Such measurements should be carried out at a viscosity ratio represented by the active reservoir viscosity ratio in order to obtain a reliable value of n. As a result of this study, it has been found that the use of low viscosity ratio gives a different relationship of *I* versus Sw compared to the high viscosity ratio. It is also found that a linear relation of *I* versus Sw is obtained at low viscosity ratio and this is due to the existence of a more uniform saturation distribution throughout the core sample. The value of saturation exponent to be used in water saturation determination should be treated with extra care since fluid characteristics created in the laboratory may not be the same as in the reservoir.

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