

**A NOVEL STUDY OF THE DIELECTRIC DISPERSION IN
POROUS MEDIA IN THE FREQUENCY RANGE
10 Hz to 10 MHz**

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ABSTRACT

Two and four-electrode setups have been developed to measure the complex impedance of partially saturated Berea sandstone, tight-gas-sand rocks, and Ottawa sand-bentonite mixtures saturated with n-decane and NaCl brine solutions. The effects of water saturation, clay content, and frequency on both the real and imaginary parts of the rock impedance are investigated between 10 Hz and 10 MHz.

A reactivity index exponent (analogous to the resistivity index exponent) is defined and shown to be related to the water saturation by an Archie-type relation. A linear relationship between the resistivity index exponent and the reactivity index exponent has been observed experimentally at frequencies below 0.1 MHz, and has been deduced algebraically as well. The reactivity index exponent can be used to estimate water saturations at frequencies above 0.1 MHz where the resistivity index exponent is found to be inadequate.

A generalized Maxwell-Wagner model, that accounts for double layer dielectric dispersion, is used to explain the experimentally observed trends. As the clay fraction is increased by a factor of 2, the dielectric constant of a simulated sand pack is found to increase by approximately the same factor at almost all frequencies from 10 Hz to 10 MHz. This linear dependence between rock dielectric constant and clay percentage has also been observed with the two-electrode data for tight-gas-sand samples of similar porosities and permeabilities. These results show the dominant effect of double layer polarization as a mechanism of dielectric dispersion in porous media in the range of 10 Hz to 10 MHz.

INTRODUCTION

Measurements of complex impedance spectra have been made in the past using mainly the two-electrode technique (Scott et al., 1967; Knight and Nur, 1987; Ruffet et al., 1991). Even though the two-electrode method of measurement is simple in principle, if not used properly, it can have many serious shortcomings such as contact polarization effects. Very little work has been conducted using the four-electrode technique at high frequencies because it involves the building of intricate circuits. The work that has been done using the four-electrode technique is in a limited frequency range and is not conducted on partially saturated rocks. Lockener and Byerlee (1985) measured the complex impedance of compacted rocks from 10^{-3} Hz to 100 Hz. Myers and Saville (1989) measured the complex impedance of colloidal suspensions at frequencies below 1 KHz, and Hoyer and Rumble (1976) used a four-electrode bridge circuit to measure the complex impedance of sandstone cores and clay water suspensions from 10 Hz to 0.1 MHz.

In this paper, we provide two and four-electrode complex impedance data for various rocks and sand packs with varying brine saturations and as a function of frequency. We then explain the experimental observations on the basis of interfacial polarization mechanisms.

EXPERIMENTAL SETUP AND PROCEDURES

Complex impedance measurements using the two-electrode technique were performed on Berea and 14 tight-gas-sand discs in the frequency range 10 Hz to 10 MHz. These discs were 3 to 10 mm thick and had a diameter of 1.5 inch. These measurements were made using an HP 16451B dielectric fixture in conjunction with an HPLCR meter 4192A LF. To completely saturate the discs, they were first saturated with CO₂ at 2,000 psi. The samples were then reevacuated and NaCl brine solution (20,000 ppm) was used to vacuum saturate these discs. Since these cores have low permeabilities, they were pressurized to 2,000 psi to ensure that brine entered all the micropores. Any residual CO₂ would dissolve in the saturating brine. The samples were weighed before and after the impedance measurements to ensure that evaporation effects were insignificant. Measurements using the two-electrode technique were performed at 100 percent brine saturation only. The two-electrode setup and measurements are detailed by Garrouch and Sharma (1992).

Four-electrode measurements were performed on Berea cores (having 22 percent porosity) and Ottawa sand-bentonite mixtures (with porosity ranging from 28 percent

to 35 percent) using a Hassler type core holder that houses 3 inch long core samples with 1.5 inch diameter. The Ottawa sand was mixed with dry bentonite powder to give 2 and 4 percent by weight bentonite mixtures. An effective radial stress of 500 psi and an axial stress of 250 psi were applied. The Berea core samples and the sand packs were vacuum saturated with a 10,000 ppm NaCl brine solution. A residual brine saturation was established in the core by dynamically displacing the brine with n-decane. Similarly, a residual decane saturation was established by displacing decane with brine. This flow sequence was repeated to check for saturation hysteresis.

An impedance analyzer measures the gain to within ± 0.1 decibels and the phase angle θ to within ± 0.5 degrees. These two quantities are then converted into impedance Z from which the resistance $R (|Z| \cos\theta)$ and the reactance $X (|Z| \sin\theta)$ of the core sample are calculated. The four-electrode circuit data is considered unreliable below 10 KHz since the measured phase angle at this frequency range was in the order of its uncertainty. The four-electrode experimental apparatus and the electrical measurement procedures are described in more detail by Garrouch and Sharma (1992).

RESULTS AND DISCUSSION

The Frequency Dependence of the Saturation Exponent

The resistivity behavior of partially saturated rocks at low frequencies is given by Archie's equation,

$$I = \frac{R_t}{R_o} = S_w^{-n} \quad (1)$$

where n is the saturation exponent and R_t and R_o are the resistivities of the partially and fully saturated rock. Figure 1 shows this relationship for data measured on Berea sandstone. As expected n values of 2.1 are obtained at frequencies below 100 KHz. At higher frequencies n decreases even though the linear trend in $\log S_w$ versus $\log I$ still persists. A summary of this data showing the variation of the resistivity index saturation exponent (n) with frequency is shown in Figure 2. The straight line drawn to determine n is based on three saturations only since the dynamic displacement technique used here provides us with uniform saturations only at a residual oil saturation (S_{or}) and at an "apparent" residual water saturation (S_{wr}). Earlier experiments conducted in our lab indicate that this straight line provides n values very close to those obtained using multiple steady state saturations (Sharma et al., 1991). This data suggests that the

relation between saturation and resistivity index with n equal to approximately 2 should only be used for frequencies below 100 KHz.

The Concept of Reactivity Index

In this study, we define the reactivity index (I^*) as the ratio of the core reactance at partial saturation (X_t) to the reactance of the core fully saturated with brine (X_0). We define the reactivity index exponent (n^*) as

$$n^* = - \frac{\text{Log}\left(\frac{X_t}{X_0}\right)}{\text{Log}(S_w)} . \quad (2)$$

The reactance X is defined as $1/\omega C_s$, where ω is the angular frequency and C_s is the rock capacitance. To check if similar trends can be observed for the reactivity index, I^* was plotted versus saturation (Figure 3) for Berea sandstone. A straight line relation is obtained between I^* and S_w on a log-log plot. The slope of this line (defined as n^*) is analogous to Archie's saturation exponent (n), taking a value of 3.5 at 10 KHz and a value of 3.1 at 0.5 MHz.

It is instructive to see how the reactivity index behavior is related to the variation of dielectric constant with saturation, discussed in the previous section. In our calculations the dielectric constant is based on a parallel resistor-capacitor model and is given by

$$k = \frac{t_a C_p}{A \epsilon_v} , \quad (3)$$

where

- κ : is the dielectric constant.
- t_a : is the sample thickness between the voltage measuring electrodes.
- A : is the cross sectional area of rock sample.
- ϵ_v : is the permittivity of free space ($8.854E-12 \text{ coul}^2/\text{Nm}^2$).

In Equation (3), C_p is the calculated capacitance of the rock assuming a parallel resistor-capacitor model and is related to the angular frequency ω , the measured series mode resistance R_s and capacitance C_s of the rock by

$$C_p = \frac{C_s}{\omega^2 C_s^2 R_s^2 + 1}. \quad (4)$$

The reactivity index has been defined earlier in terms of the reactances and can also be defined as the ratio of the series mode capacitance of the fully water saturated core (C_o) to the series mode capacitance of the partially water-saturated core (C_t). Assuming a relationship between dielectric constant and water saturation given by Hoyer and Rumble (1976) as $k = k_{100} (S_w)^p$, Equations (3) and (4) yield

$$\text{Log} \frac{C_o}{C_t} = -p \text{Log} S_w - \text{Log} \left(\frac{(\omega C_t R_t)^2 + 1}{(\omega C_o R_o)^2 + 1} \right). \quad (5)$$

Here κ_{100} is the effective dielectric constant at 100 percent water saturation, and the coefficient p is approximately equal to 1. As shown in Figure 4, the terms $(\omega C_t R_t)^2$ and $(\omega C_o R_o)^2$ are much greater than unity at frequencies below 0.1 MHz. With this approximation ($(\omega CR)^2 \gg 1$), a linear relation between the saturation and the reactivity index is obtained on a log-log plot. Substituting Equations (1) and (2) in Equation (5), and using the definition of the reactivity index the following relation between the reactivity index exponent (n^*) and the resistivity index exponent (n) is obtained,

$$n^* = 2n - p. \quad (6)$$

Equation (6) clearly illustrates the reason the reactivity index exponent is in general larger than the resistivity index exponent. Since n is approximately 2 for the water-wet Berea, n^* will be approximately 3 under the assumptions made in deriving Equation (6). This is what is observed in the experiments for both Berea and sand-bentonite mixtures, at frequencies less than 0.1 MHz. The reactivity index exponent (n^*) of the water-wet Berea is approximately 3.5 at 10 KHz (Figure 3), corresponding to a resistivity index (n) of approximately 2.1 (Figure 1), at the same frequency. This is also consistent with Equation (6).

The Effect of Clay Content

A generalized Maxwell-Wagner theory that accounts for double layer dielectric dispersion (Lima and Sharma, 1992) has been used to investigate the effects of increasing the clay fraction on the dielectric constant. As the clay fraction is increased

by a factor of 2 and 3, the dielectric constant of a simulated sand pack increased by approximately the same factor at almost all frequencies from 10 Hz to 10 MHz (Figure 5). Similar results were observed with the two-electrode data for shaly-sand rock samples (Figure 6). For samples of similar porosities and permeabilities, the dielectric constant appeared to depend linearly on the clay content. These results show the dominant effect of double layer polarization as a mechanism of dielectric dispersion in porous media in the approximate range of 10 Hz to 10 MHz. These double layer effects are well documented for suspensions of colloidal particles in aqueous electrolyte solutions. These effects are known to display high dielectric constants in the presence of low frequency alternating fields (Schurr (1964); Chew and Sen (1982); Springer et al. (1983)). The application of an external oscillating electric field disturbs the symmetry of double layer on the particles by causing the positive ions to move in the direction of the field and polarize at one end, and the negative ions at the other. This polarization enhances the dielectric constant because a large dipole is created as a result of the asymmetric distribution of charges.

CONCLUSIONS

Measurements were made for the impedance of both fully and partially-saturated rocks using four-electrode and two-electrode setups. These measurements include both clean and shaly-sand samples.

For partially saturated rocks, the saturation exponent (n), obtained from the resistivity index-saturation curves, is found to vary with frequency above 100 KHz. Resistivity measurements from well logs operating at this particular frequency and above may be used to estimate the water saturation in hydrocarbon formations but with a modified saturation exponent. In particular, resistivity inferred from the LWD log (operating at 2 MHz) and the DPT log (operating at 25 MHz) should not be used in the Archie relations with $n=2$ to estimate the water saturation in porous media. A reactivity index exponent (n^*) has been defined here and can be used instead to estimate the water saturation.

For fully saturated rocks, the dielectric constant is found to increase with the clay volume fraction, and to decrease with increasing frequency. The experimental results of this study are interpreted through a double layer polarization shaly-sand model. The data presented clearly shows that properties such as water saturation, clay content and grain size can be obtained from LWD logs, or from other electrical measurements made above 2 MHz.

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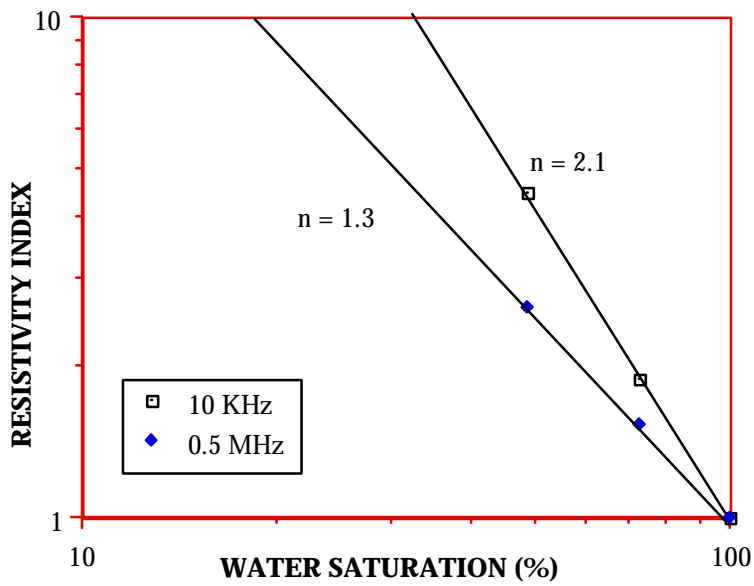


Figure 1: Resistivity index versus water saturation for water-wet Berea saturated with n-decane and 10 000 ppm NaCl brine at two different frequencies (four-electrode measurements).

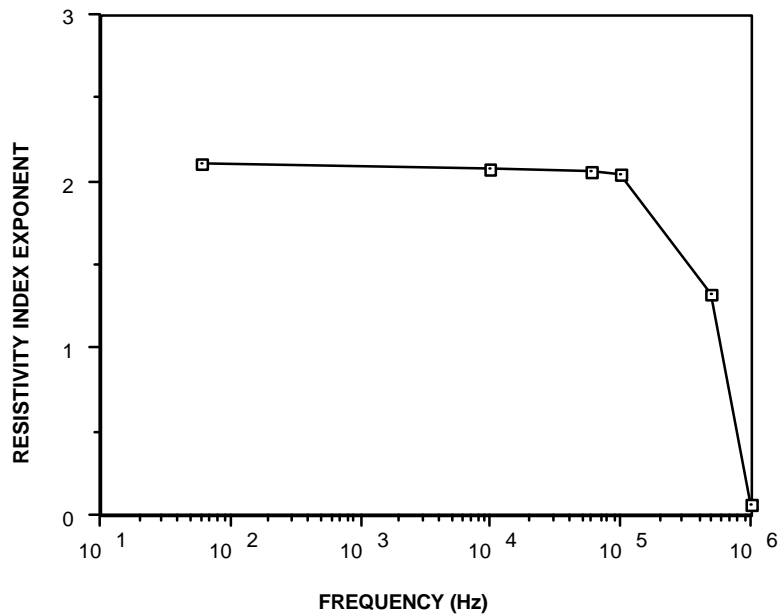


Figure 2: Resistivity index exponent versus frequency for water-wet Berea saturated with n-decane and 10 000 ppm NaCl brine (four-electrode measurements).

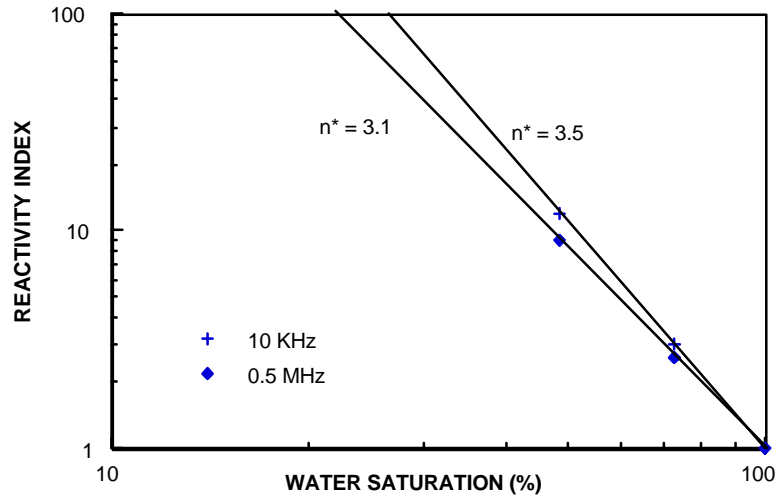


Figure 3: Reactivity index versus water saturation for water-wet Berea saturated with n-decane and 10 000 ppm NaCl brine at two different frequencies (four-electrode measurements).

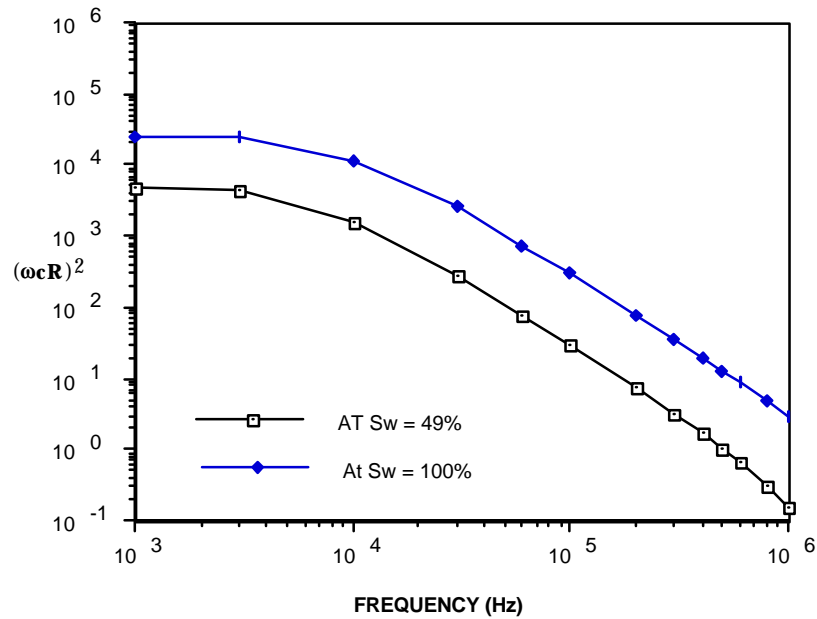


Figure 4: Experimentally measured $(\omega cR)^2$ versus frequency for water-wet Berea at two different brine saturations (four-electrode measurements).

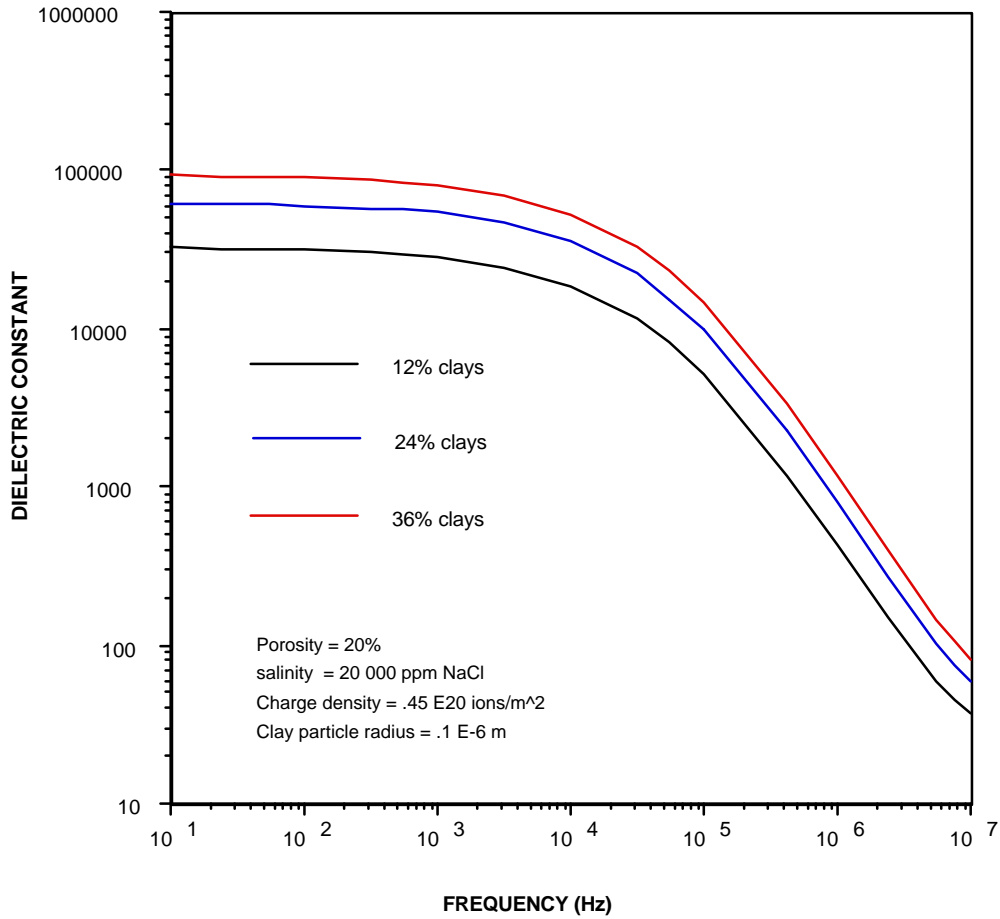


Figure 5: Dielectric constant versus frequency for simulated sand-packs with different clay content saturated with 20 000 ppm NaCl brine.

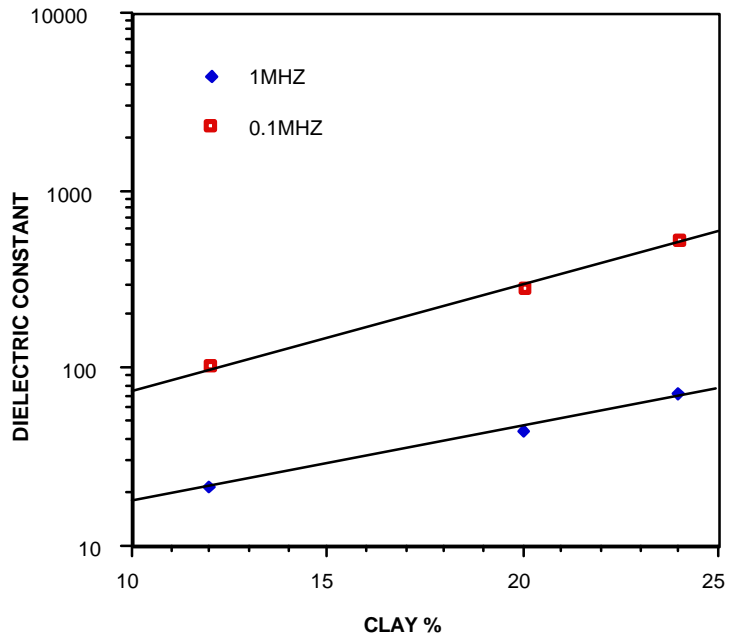


Figure 6: Dielectric constant versus clay percent for tight-gas-sand samples of 13% porosity and 0.03 md permeability at multiple frequencies. Samples were saturated with 20 000 ppm NaCl brine: two-electrode measurements.