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Study of the low-frequency dispersion of permittivity and resistivity in tight rocks

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ABSTRACT

The road to understanding the frequency dispersion (relaxation) of permittivity and resistivity in tight rocks remains relatively uncharted. Our team from Da'anzhai Group, Jurassic formation, Sichuan Basin carried out practical research to explore this phenomenon. The research was conducted under laboratory conditions for a selection of low frequencies, with ranges between 0.1 Hz to 1 kHz.

Our research has shown that, although both the permittivity and resistivity decrease as the frequency increases, the two individual metrics display different behaviours when compared with each other. While the degree of resistivity variation is minimal, to the point that it is redundant, the permittivity, on the other hand, demonstrates something that is scientifically noteworthy. Permittivity has a distinctive dispersion degree across the entire sample of frequencies and the difference between the minimum and maximum frequencies is several orders of magnitude. An additional, and unexpected, learning from our research is that the level of frequency dispersion increases as the water saturation and concentration increases.

In this paper, a collection of equations has been formulated to describe this relationship. These equations particularly shed light on the areas of rock porosity and saturation. They also show that the degree of frequency dispersion of permittivity or resistivity can be used as a function of water saturation and concentration.

Two new variables are introduced here, D_R and D_C, to demonstrate the relaxation law quantitatively. In our practical research, we have characterised the relationship between the saturation and concentration with dielectric relaxation, using three different concentrations of D_R and D_C and five different saturations of NaCl solution. In difference to conventional Archie's multiple experimental parameters, we have established a new formula to derive the saturation from Rp and Cp, or from D_R and D_C directly. Two important frequencies were also further investigated for Cp dispersion: first is the critical frequency, which marks the dispersion speed change from steep phase to steady phase, and second is the zero-frequency, which marks the dispersion when it approaches zero. All tight rocks were measured under the same conditions, with the results displaying the same pattern of variations. The results have led us to believe that Cp's frequency dispersion at low-frequencies provides a new methodology to characterise tight rocks.

1. Introduction

Permittivity and resistivity are crucial physical rock parameters that govern the propagation of electromagnetic fields (EMFs) in porous rocks. Rock resistivity has been a research subject for centuries, with enormous numbers of dedicated articles published throughout the years. G.E. Archie first presented his litho-electric experiment results and offered an equation to bridge the missing gap between resistivity and saturation of rocks in 1942. Subsequently, it was then possible to qualitatively evaluate the fluids, as well as quantitatively calculate the amount of water and hydrocarbons in rocks. The resistivity and permittivity of a rock are commonly known as the functions of its chemical composition. This in turn can be used to measure rock properties such as, density, porosity, water saturation, inhomogeneity, polycrystallinity, lithology and component geometries. These rock properties are related to the shape of the particles; particle size distribution (or rock texture) and rock bulk density. (Alex and Behari, 1996, Alex and Behari, 1998; Wang et al., 1983; Pelton et al., 1984; David and Kevin, 2001; Seleznev et al., 2004). However, it's hard to evaluate the exact contribution of each aspect to a sample's dielectric constant, with water saturation (including both bound and free water) being the key factor in affecting the rock's permittivity.

The frequency dispersion of complex dielectric constants provides valuable information for any scientists researching rocks properties, such as geophysicists and petrophysicists. Most published researchers have base their studies on using high frequency collection, usually

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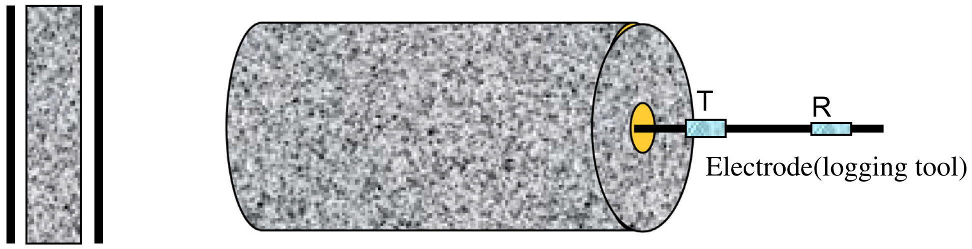
Nomenclature

F	frequency, Hz.
C_w	concentration of NaCl solution, mol/L;
C_p	permittivity, F/m;
R_p	resistivity, Ω·m;
K	electrode coefficient, cm;
S_w	saturation of water;
D_R	dispersion exponent of resistivity, dimensionless;
D_C	dispersion exponent of permittivity, dimensionless;
A	coefficient of resistivity, Ω·m;
B	coefficient of permittivity, F/m;
Kc	slope of permittivity frequency dispersion, dimensionless;
f_1	point-one frequency, Hz;
f_0	point-zero frequency, Hz;

between the range of kHz to MHz, or even GHz (Clark et al., 1988, 1990; Bonner et al., 1995; Seleznev et al., 2004, Seleznev, 2006; Anderson et al., 2006, 2008; Revil, 2013). However, the reoccurring behaviours of low-frequency dispersion (LFD), which are widely observed in many materials, were not fully recognized until it was discovered and further investigated in a comprehensive study conducted by the Chelsea Dielectrics Research Team (Jonscher, 1983). These behaviours were explained with expert precision in their renowned book Dielectric Relaxation in Solids (D_{RS}). Earlier studies proved that most rocks and minerals display distinct dielectric dispersion in the low-frequency region from a few Hz to several MHz (Saint-Amant and Strangway, 1970; Knight and Nur, 1987; Wu et al., 1999). At low frequencies, the dielectric dispersion of geological materials is believed to be initiated by the polarisation associated with charge build-ups at the grain boundaries or grain imperfections. Additionally, grain sizes and their distribution of the geological samples also has an impact on the frequency-dependent ε' values (Feng and Sen, 1985; Lesmes and Morgan, 2001). Multiple researchers have confirmed that rocks and other geological materials exhibit the Cole and Cole (1941) dielectric dispersion at low frequencies (Saint-Amant and Strangway, 1970; Taherian et al., 1990; Dias, 2000; Lesmes and Morgan, 2001; Sengwa et al., 2004; Toumelin and Torres-Verdín, 2009). Although the Cole-Cole model has been universally used as the equation to depict the polarisation and relaxation processes, there are still certain mechanisms that have not been entirely understood and or explained.

Mehdi Hizem et al. have summarised three types of polarisation in rocks: electronic, orientational and interfacial, respectively. In their research, it was noted that the predominance of these regimes depends on the frequency of the external electric field. The electronic polarisation, which corresponds to rock permittivity, occurs at a range of 1 Hz to 1×10^8 Hz; molecular orientation, corresponding to water molecular permittivity, takes place at a range of 1 Hz to 1×10^{10} Hz; and interfacial polarisation, corresponding to pore geometry and ions, occurs at a range of 1 Hz to 1×10^{16} Hz.

Some researchers have illustrated that the permittivity dispersion bears sufficient amounts of information when at low-frequency domains, such as the matrix, shale, fluid and pores, and even the geometry of the pores, their distribution, and the connectivity of the pore



(a) conventional capacitor (b) formation capacitor

Fig. 1. Capacitors with different configuration. (a) conventional capacitor, whose spacing between two plates are much less than the length of plate, and this configuration can reduce the fringing effect. (b) shows a true formation capacitor, the electrodes(T, transmitter; R, receiver) usually located in logging tools, its spacing is much smaller than the size of formation. Therefore, in practice, this kind of capacitor is very different with standard capacitor.

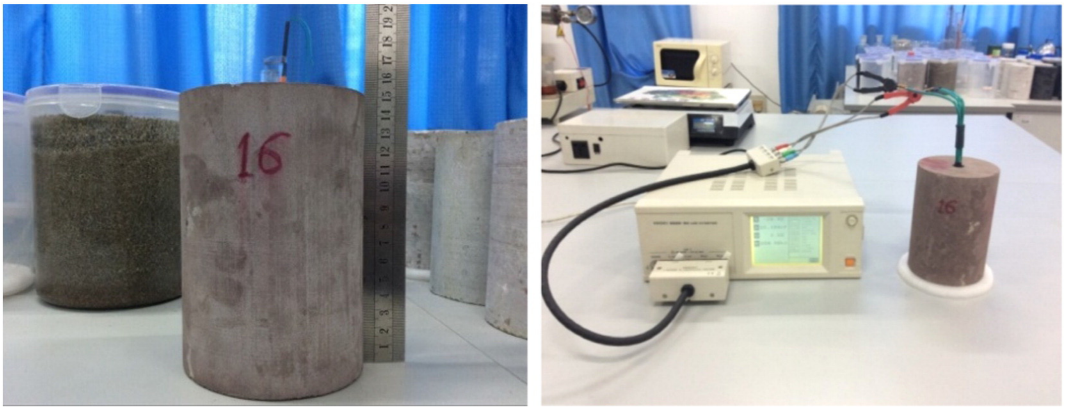


Fig. 2. Tight rocks sample with dimensions of 15 cm in height and 10 cm in diameter, with a mid-hole of 1.5 cm in diameter. Left: No. 16 was drilled from Daanzhai Group, Jurassic formation, middle region of Sichuan Basin. Its porosity is approximately 5.90%, permeability is approximately 0.013×10^{-3} μm^2. Right: to ensure the measurement results, a special electrode made from carbon fibre was placed into the mid-hole, and mud fluid was also injected into it, this measurement method is very similar to the in-situ operation.