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Dielectric constant measurements of sweep frequency and its effect from 20 MHz to 1000 MHz

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ABSTRACT

The array dielectric tool (ADT) can be used in situations where the formation water resistivity is variable or unknown and allows for obtaining Archie's cementation exponent (m) in combination with other porosity logging methods. However, few laboratory measurements of the dielectric dispersion properties at wide frequencies (20 MHz–1000 MHz) have been shown till now, which hinders our understanding of the petrophysical mechanisms. In this study, we introduce the dielectric constant measurements of a sweep frequency in the range of 20–1000 MHz based on the parallel-disk capacitor method. In order to easier control the variables, such as the m and the porosity, artificial cores with changeable m values were manufactured from glass beads. The relationships between the core dielectric constant and the frequency, saturation, salinity, and pore texture were investigated in the MHz to GHz range. It is shown that the frequency, water saturation, salinity, and pore texture affect the dielectric dispersion of cores. Additionally, a modified formula for predicting m with a high-frequency dielectric constant was developed based on core sample data. This study provides a better understanding of the dielectric dispersion mechanism and the modified formula for calculating m can improve the analysis of well log data.

1. Introduction

The conductivity and dielectric constant constitute the main electrical properties of formations in the field of well logging. In the past decades, resistivity and induction tools have been proven useful for the quantitative evaluation of formations because the conductivities of oil and gas are usually much lower than that of the connate water in the formation. However, these tools are not applicable when the formation water resistivity is variable or unknown especially for heavy oil reservoirs where fresh water (low salinity) causes a low resistivity contrast between oil and water (Shen, 1985; Shen et al., 1985). Fortunately, the large difference of the dielectric constant between oil (about 1–3 units) and water (about 80 units) makes a quantitative assessment of the relative contents of oil and water possible. Since the 1980's, there has been an increased interest in wireline dielectric measurements and many dielectric tools were developed, such as the electromagnetic propagation tool (EPT), the deep propagation tool (DPT), and the high-frequency dielectric logging (HFD) (Calvert, 1974; Wharton et al., 1980; Huchital, 1980; Cheruvier and Suau, 1986; Rau et al., 1991). However, these tools were not widely used due to several limitations including hole rugosity, high salinity, and simple response algorithms (Mude et al., 2010). Since 2010, the new generation dielectric tool called the array dielectric tool (ADT) manufactured by Schlumberger has overcome these limitations and can provide additional information for more accurate evaluation of the formation. Moreover, one revolutionary advance of the tool is the continuous measurement of the dielectric dispersion and a multi-spacing antenna array operating at multiple frequencies in the MHz to GHz range (Hizem et al., 2008). However, few laboratory measurements of the dielectric dispersion properties at wide frequencies (20 MHz–1000 MHz) have been reported to date, hindering our understanding of the petrophysical mechanisms.

Different techniques exist for measuring the dielectric constant at different frequencies and can be used to understand the mechanism of dielectric dispersion. At frequencies lower than 20 MHz, the electrode method is usually used. Many people have reported these types of

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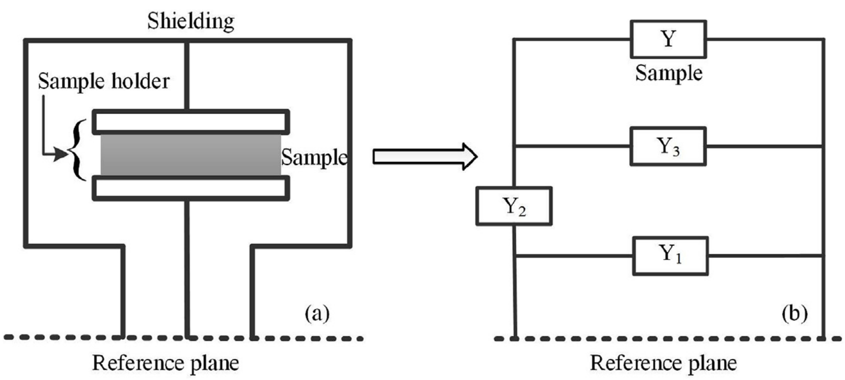

Fig. 1. Schematic of the sample holder and shielding structure and its equivalent circuit. (a) Parallel-disk sample holder; (b) equivalent circuit of π type.

measurement results. Knight and Nur (1984, 1987) measured the dielectric constant of sandstones as a function of saturation and frequency in the range of 5–13 MHz using a two-electrode technique with platinum electrodes sputtered onto the flat faces of disk-shaped samples. Garrouch and Sharma (1994) described the influence of the clay content, salinity, stress, and wettability on the dielectric properties of brine-saturated cores in a frequency range of 10 Hz–10 MHz using two-electrode and four-electrode techniques.

At frequencies higher than 20 MHz, parallel-disk capacitors are commonly used. Mazzagatti et al. (1983) measured the dielectric constant of carbonate cores saturated with brine using a parallel-disk capacitor in the frequency range of 20–100 MHz. Shen et al. (1987) and Shi and Shen (1989) developed the quasi-static electromagnetic theory of the parallel-disk sample holder used to measure the conductivity and the dielectric permittivity of dissipative materials. When the frequency is close to the GHz range, this method is easily affected by the residual impedance and edge capacitance effects. Therefore, coaxial line methods were developed for dielectric constant measurement at ultra-high frequencies (Nicolson and Ross, 1970; Weir, 1974; Poley et al., 1978; Stuchly and Stuchly, 1980; Lange, 1983; Shen, 1985; Shen et al., 1985; Feng et al., 1986; Zheng and Smith, 1991; Wu et al., 2011). The advantage of this method is that the slot on the outer conductor is not required. Also, the scattering matrix parameters can be measured automatically by a special instrument called the S-parameter Test Set ™.The disadvantage of this method is that the core sample must be machined precisely to fit the coaxial line. Therefore, it is not appropriate for unconsolidated cores. For single frequency measurement, the resonant-cavity method is used to measure the low-loss material and the results can be highly precise (Barlow and Rickard, 1959). But the heavy volume and single measurement frequency (higher than 800 MHz) of the resonant cavity cause failures when wideband measurements are obtained.

In light of the pros and cons of the four above-mentioned methods, the parallel-disk capacitor was used in our study not only the core sample processing has a low requirement but also the frequency range of the measurements is close to that of the ADT. One notable problem is that the measurement results are easily affected by the residual impedance and edge capacitance effects of the sample at frequencies higher than 700 MHz (Zhang, 2016); therefore, a modified sample holder is developed to overcome this problem.

In order to easier control the variables, such as Archie's cementation exponent (m) and the porosity, artificial cores with different values of m were manufactured from glass beads in our experiments. The relationship between the core dielectric constant and the frequency, saturation, and salinity was investigated in the range of 20–1000 MHz in order to clarify the petrophysical mechanisms. This study is undertaken to establish a wide-frequency database for the dielectric properties of cores to expand on data provided in the existing literature.

Additionally, many reports have indicated that the dielectric constant of the core is dependent not only upon the dielectric properties of the constituent materials but also upon the geometrical distribution of those materials (Sen, 1980; Sherman, 1983); however, the effect of the pore texture, such as the m is not clear yet. The artificial cores with changeable m values show great advantages in this situation. Once the parameters are controllable, the effects between porosity and m value on dielectric dispersion can be easily analyzed. Finally, a modified formula for predicting the values of m with high-frequency dielectric constant measurements was developed based on core sample data.

2. Theory of dielectric constant measurements

The dielectric constant measurement system of the sweep frequency consists of an impendence analyzer, a sample holder, and a computer with peripherals. The frequency of the impendence analyzer (E4991B) ranges from 1 MHz to 3 GHz. The parallel-disk sample holder is usually shielded with a metallic housing in order to prevent the leakage of electromagnetic fields (Shen et al., 1987). Fig. 1a shows the simplified structure of a parallel-disk sample holder enclosed in a rectangular shielding.

The shielding can be viewed as a radially enlarged section of a coaxial line; one end connects to the parallel-disk sample holder and the other end to the coaxial line at the measurement reference plate (Mazzagatti et al., 1983). Therefore, the shielding is equivalent to a two-port network and it can be considered as a "π network" with the elementsY_1, Y_2, and Y_3 without losing generality (Fig. 1b). The three parameters Y_1, Y_2, and $Y_3$of the π-type circuit can be measured at each frequency using Eq. (1) (Shen et al., 1987).

Before measuring the admittance of the core samples$Y$, air, Plexiglas, and brass are used as the standard samples and the admittances of the air, Plexiglas, and brass are Y_a, Y_p, Y_b respectively. The admittance of the standard samples was measured in the reference plane, and the results areY_{ma}, Y_{mp}, and Y_{mb} respectively. Therefore, the three parameters of the π-type circuit (Y_1, Y_2, Y_3) can be determined by Eq. (1).

$$\begin{cases} Y_{ma} = Y_1 + \frac{Y_2Y_3 + Y_2Y_a}{Y_2 + Y_3 + Y_a} \\ Y_{mp} = Y_1 + \frac{Y_2Y_3 + Y_2Y_p}{Y_2 + Y_3 + Y_p} \\ Y_{mb} = Y_1 + \frac{Y_2Y_3 + Y_2Y_b}{Y_2 + Y_3 + Y_b} \end{cases} \tag{1}$$

Subsequently, the admittance of the core sample Y_{mu} is measured in the reference plane and the true admittance of the samples Y can be obtained by Eq. (2) and Eq. (3). The effect of shielding has been eliminated by Y_1, Y_2, Y_3. Therefore, the measured admittance of the samples is not affected by the edge field.

$$Y_{mu} = Y_1 + \frac{Y_2Y_3 + Y_2Y}{Y_2 + Y_3 + Y} \tag{2}$$

$$Y = \frac{Y_2Y_3 - (Y_2 + Y_3)(Y_{mu} - Y_1)}{Y_{mu} - Y_1 - Y_2} \tag{3}$$