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Dielectric permittivity spectra of oil–water-saturated sandy-clayey rocks of different mineralogical compositions and relaxation properties of water in these rocks

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Abstract

Experimental measurements of the dielectric permittivity and equivalent conductivity of sandy-clayey samples (a mixture of river sand with bentonite or kaolin) saturated with salt-solution–diesel-fuel emulsions were performed in the frequency range from 10 kHz to 1 GHz at temperatures of 25–65 ºC. It is shown that when the content of the salt solution in the saturating fluid does not exceed 10%, the dielectric permittivity in the frequency range from 1 MHz to 1 GHz depends little on the mineral composition of the sample and on the concentration of the saturating solution. When the portion of water is 33.3% or higher, increasing the concentration of the salt solution leads to an increase in the equivalent conductivity and the real part of the complex dielectric permittivity. Using the refractive model of the complex dielectric permittivity, we have estimated the dielectric properties of bound water, which depend on temperature and the type of clay (bentonite or kaolin) in the sand–clay mixture but are independent of the water saturation and the amount of clay in the sample.

Keywords: oil-bearing deposits; sandy-clayey rocks; dielectric permittivity; conductivity; multifrequency dielectric relaxation

Introduction

Knowledge of the dielectric characteristics of rocks in the frequency range from hundreds of kilohertz to several gigahertz is required to develop electromagnetic methods of geological exploration, including those using ultrawideband pulses, for subsurface sounding, for accurate geosteering in drilling horizontal wellbores, and in developing methods for dielectric logging (Aksel'rod, 2007; El'tsov et al., 2014; Epov et al., 2007, 2014).

Results of measurements of the dielectric permittivity and conductivity of sand and clay saturated with an oil–salt solution mixture over a wide frequency range are given in papers (Epov et al., 2009, 2011). In the first of these, frequency spectra of the complex dielectric permittivity $\varepsilon' - i\varepsilon''$ (CDP) were simulated using a refractive model (Mironov et al., 2004) which provided a good description of CDP spectra of mixtures based on sand and gave a considerable discrepancy with the experimental data for mixtures based on bentonite clay. This was due to the significant influence of interlayer polarization at the water–solid interface at frequencies below 1 GHz, resulting in a significant increase in the real and imaginary parts of the CDP in clayey rocks with a high specific surface area. In the second modeling study of CDP interlayer polarization in the sample was taken into account by two regions of dielectric relaxation described by the Cole–Cole model.

A dielectric model whose input parameters are the water content, temperature, and thermodynamic properties of water has been developed (Epov et al., 2012) based on the results of measurements of spectra of partially water-saturated broken rocks containing less than 16% clay minerals. Assuming that the relaxation phenomena in the presence of the interface are due to the dielectric properties of bound water, it is possible to develop a dielectric refractive model in which the increased CDP of rocks at low frequencies is mainly explained by an increase in the CDP of bound water (Mironov et al., 2013a,b).

The frequency and temperature dependences of the CDP of oil-and-water saturated samples based on a mixture of bentonite and river sand in equal proportions by weight,

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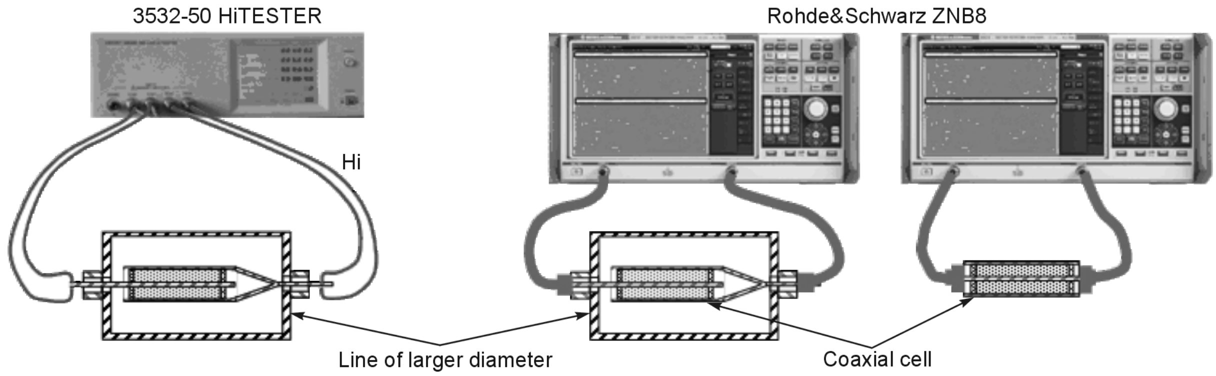

Fig. 1. Experimental setup for measuring CDP in a single cell in a wide frequency band.

saturated with formation water–diesel fuel mixtures were measured in (Bobrov et al., 2013a), and in (Repin et al., 2013), these findings were supplemented with data for 70/30 bentonite–river sand samples saturated with a salt solution–diesel fuel emulsion at various concentrations of the salt solution. It has been shown that in the frequency range from 1 to 1000 MHz, the relaxation properties of bound water in mixtures containing bentonite as the clay fraction are almost independent of the bentonite content and the salinity of the solution and the CDP of the samples depends on the content of bound water, i.e. on the specific surface.

In this paper, we present the results of measurements of the CDP of samples containing sand, bentonite, and kaolin. Using the refractive model, it is shown that the CDP of bound water in these samples depends on the mineralogical composition. We also studied samples with high water saturation in which part of the water was not bound on the surface of mineral particles. For this bulk water, the relaxation parameters of the model were also obtained.

Experiment

The CDP of samples in the frequency range from 10 MHz to 1 GHz were measured using ZVRE and ZNB8 (Rohde–Schwarz) vector network analyzers. The measuring cells were coaxial-line segments with a diameter of 7/3 or 16/7 mm mm and a length of 2 to 10 cm. At frequencies above 50 MHz, the complex transmission factor of the cell connected to the vector network analyzer was measured (Fig. 1). The CDP was calculated using the method described in (Epov et al., 2011). For measurements in the range from 0.3 to 100 MHz, the same coaxial cell was connected into a break in the central conductor of a coaxial line segment of larger diameter, and the complex transmission factor of this segment was measured. The measurement technique is described in (Bobrov et al., 2012; Bobrov et al., 2015). At frequencies below 5 MHz, the line segment with the cell was connected to a 3532–50 HiTESTER (HIOKI) impedance meter. The CDP of the test sample was calculated by the method described in (Epov and et al., 2011). The temperature dependence of the CDP was measured using a TH-ME-25 climate chamber (South Korea) with a temperature setting accuracy of 0.3 K.

In the overlapping frequency ranges 50–100 MHz and 0.3–5 MHz, the difference between the results obtained by different methods was less than the measurement error, which for the real part of the CDP ε' in the frequency range 10 kHz–1 GHz for samples with a low-frequency equivalent conductivity $\sigma_e \le 0.1$ S/m was 0.7–5%, increasing to 6–7% at frequencies of about 1 MHz and 1 GHz. Higher error was observed in measurements of rocks with a conductivity of 0.5–1.0 S/m in the frequency range from 5 to 10 MHz, and it reached 12%. The measurement error of the imaginary part of the CDP ε'' did not exceed 3% over the entire range of frequencies.

The frequency range is limited from below by the effect of electrode polarization. The boundary frequency at which this effect can be neglected was determined by measuring the impedance of the cell at low frequencies for different signal voltages from 0.1 to 1.0 V. Since the electrode polarization is voltage-dependent, the absence of voltage dependence of the measured impedance indicates that it is not affected by the electrode polarization. The experiment showed that at an equivalent conductivity of the sample at a frequency of 20 kHz, $\sigma_e = 0.1$ S/m, the deviation of the measured values of the real part of the CDP ε' from the average value varies from 10% at a frequency of 100 Hz to 1.2% at a frequency of 10 kHz, to 0.6% at a frequency of 20 kHz, and to 0.3% at a frequency of 50 kHz. The maximum instrumental error in measurements by the 3532–50 HiTESTER device at these frequencies is 1.3–1.5%. Thus, even at a frequency of 10 kHz, the influence of electrode polarization is insignificant and comparable to the instrumental error of 3532–50 HiTESTER, and at a frequency of 50 kHz, it is absent. At an equivalent conductivity of the sample $\sigma_e = 0.01$ S/m, the influence of electrode polarization is absent at frequencies above 20 kHz.

Samples were prepared as follows. Predried river sand and clay (bentonite and kaolin) were first mixed in the desired ratio. Then, a formation water–diesel fuel emulsion was prepared in different ratios using a small amount of Domul'tal emulsifier. Preliminary measurements showed that the diesel fuel was similar in dielectric properties to oil at all frequencies.