Effect of the Rock/Water/Air Interaction on the Complex Dielectric Permittivity and Electromagnetic Waves Attenuation in Water-saturated Sandstones

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Abstract— The results of the experimental measurements of the complex relative permittivity (CRP) of the water-saturated powders of the quartz granules of different size and solid sandstones are given in the frequency range from 0.1 kHz to 1 GHz. It is shown that when the water content decreases in the powders of the fine granules and solid sandstones at the determined frequency band the increasing of the real part and decreasing of the imaginary part of the CRP are observed. This leads to the significant increasing of the skin layer, that reaches the highest values at the water content of about 60–80% of the full saturation.

In the literature, for example in [1], the properties of elastic waves in the water-saturated sandstones, particularly the dispersion and attenuation, were described in details, but the properties of electromagnetic waves were described insufficiently. It is known that the real part of complex relative permittivity (CRP) of sedimentary rocks containing clay roughly increases at frequencies below 1 GHz [2–4]. The reason is in the multifrequency relaxation processes. In completely saturated sandstones the real part of complex relative permittivity (CRP) depends on the porosity and it remains almost constant in the frequency range of 1 MHz to 1 GHz. At frequencies below 1 MHz observed abrupt increase due to the relaxation of the double layer at the rock-water interface.

It is usually assumed that reduction of water content in the rock reduces the real part of CRP. Though there are a number of works which shows the deviations from the tendency in some cases [5–7].

We measured CRP of water-saturated powders of the quartz granules and solid sandstones with a porosity from 7% to 40% in the frequency range from 100 Hz to 1 GHz by using the method described in [8]. The measurement error at different frequencies was from 0,2 to 3% for ε' and ε''.

The schematic illustration of the experimental setup is given in Fig. 1. The complex dielectric permittivity was measured in the frequency range from 0.1 kHz to 1 GHz with Rohde & Schwarz ZNB8 vector network analyzer (VNA) and the LCR-meter 3532-50 Hioki HiTESTER. Depending on the measured frequency range, the same cell was either directly connected to the VNA (for measuring in the range from 100 MHz to 1 GHz) or included into the break of the central conductor of a coaxial line of a large cross section (for measuring in the range from 300 kHz to 100 MHz). At frequencies below 1 MHz, the cell admittance was measured ordinary by the LCR meter. CRP of the solid samples was measured in the range of frequencies from 100 Hz till 100 MHz

The characteristics of the investigated samples are in the Table 1.

Table 1: The characteristics of the investigated samples.

No.	The characteristics of the samples	The average diameter d, (μm)	The d RMSE (μm)	The porosity	The dry density (g/cm^3)
1	Powders of the quartz granules	1,35	0,42	0,434	1,50
2		29,6	11,9	0,327	1.58
3		54,5	11,6	0,420	1.57
4		71,5	17,6	0,392	1.60
5	Solid sandstones			0.173	2.21
6				0.068	2.27

The results of the measurements of the real part of the CRP of the completely deionized water-saturated samples that are shown in the table are given at Fig. 2. The temperature here and furthermore is 25°C.

At frequencies upper 1 MHz the values of ε' of the large granules powders (samples 2–4) don't almost depend on frequency and they are determined by general porosity. Sample 1 consisting of fine granules contains the considerable part of bound water on the rock-water interface. At frequencies higher than 100 MHz, the dielectric permittivity of this form of water is determined by oriental polarization of water molecules and it is significantly less than the free water has [8]. At frequencies below 1 MHz the main role plays the polarization in the double layer at the rock-water interfaces, that is why the more the specific surface area (the less the pore size) the higher the ε'.

In the solid samples the porosity is far less therefore the dielectric permittivity ε' is less at frequency of 100 MHz. For all the samples except the sample 1 there is dependence between general porosity and ε' and the square of the correlation coefficient ($R^2 = 0.97$) that is close to linear. The increasing of the ε' while decreasing of the frequency begins earlier than in the powders of the quartz granules and obeys another law. Evidently the defining role plays not only the pore size but their form.

The CRP frequency dependence of the samples at different saturation levels is similar to the dielectric relaxation, described by the models of Debye or Cole-Cole.

At certain frequency range the real part of CRP is bigger than the one of the completely saturated samples, but the imaginary part of ε'' sharply decreases. It is necessary to note that experimental results that could be treated as the result of the dielectric relaxation were given earlier in works [4–6] as a rule at limited frequency range.

The frequency dependencies for ε' and ε'' for different saturation levels of the quartz granules powders are shown at the Figs. 2, 3. At high frequencies about 1 GHz within the water saturation level K_W increasing the values of ε' are monotonically raising. At the same time the values of ε' and ε'' in powders of granules of different size for the relevant values of K_W are almost identical.

In the samples containing the fine granules ($r \leq 54.5\,\mu$m) at frequencies of 100 kHz–20 Hz there is a strong influence of relaxation process when K_W is between 0.2 and 0.9. The values of ε' are much bigger than at the completely saturation (Fig. 2), but the values of ε'' are much smaller. The reason of the relaxation process is in interlayer polarization at the water-air bound.

While increasing the size of granules (and consequently the size of pores) the relaxation process area moves down the frequency. Thus the rising of ε' at the decreasing of water saturation level is at frequency range of 50 kHz–12 MHz in the sample No. 2, and at the same frequency range there is only the upper bound of relaxation process in the sample No. 4 at frequency about 20 kHz (Fig. 2). Unfortunately the theoretical dependence of the relaxation time on the pore size wasn't found yet.

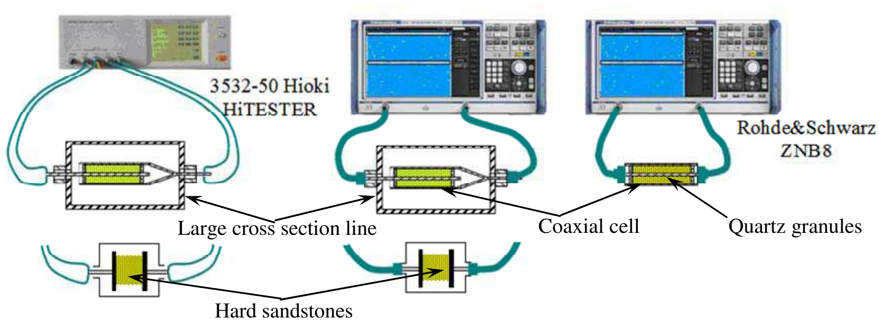


Figure 1: Schematic illustration of the experimental setup to determine the frequency dependence of the CRP.

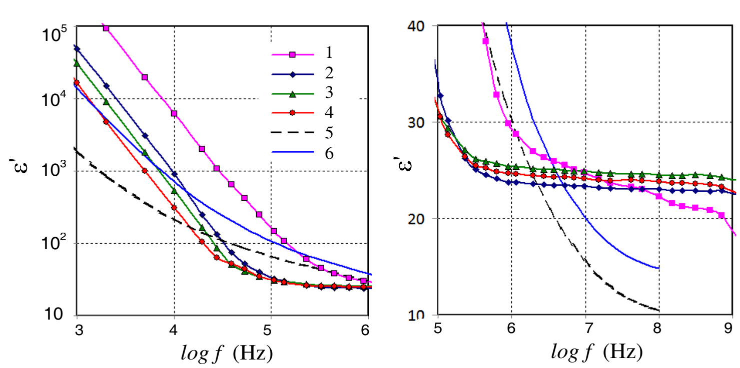


Figure 2: Real part of the dielectric permittivity of the completely saturated samples. The numbers of the curves correspond to the numbers of the samples from Table 1.

The spectra of ε' and ε'' for the solid sandstones (sample No. 6) are given in Fig. 3. The difference from the CRP of the powders of granules is caused by lower general porosity of the solid sandstones. Firstly the values of ε' and ε'' are both much smaller at high frequencies than in the powder samples, which can be explained by lower volume content of water. Secondly the values of ε' of the solid sandstones are higher at relaxation process areas than in the powders.

Thirdly at frequencies lower than the band of the dielectric relaxation the values of ε'' are one-two orders of magnitude less. In spite of the fact the water content in solid sandstones is several times less, the maximum values of ε' at relaxation areas are reached at the same values of K_W that are in the powders.

At the dielectric relaxation band at $K_W = 0.6$–0.8 when the values of ε' increase and the values of ε'' decrease there must be reduction of the electromagnetic wave attenuation and the extension of the skin layer thickness. The calculated values of the skin layer thickness are given in the Fig. 4.

In the powders of quartz granules (sample No. 2) the highest values of the skin layer thickness are at frequencies below 20 MHz and $K_W = 0.6$–0.8 ad these values are higher than in sample No. 4 (see the Fig. 4(a)). The reason is in the absence of dielectric relaxation in the powders with a large size of granules at the investigated frequency range, the skin layer thickness monotonically reduces

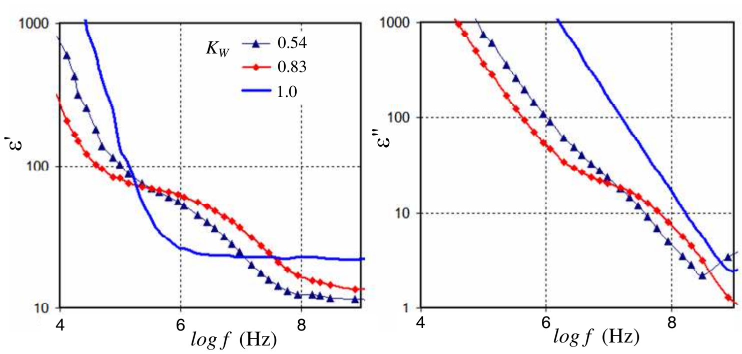


Figure 3: Dielectric permittivity ε' and ε'' of the sample No. 2, saturated with deionized water at different K_W.

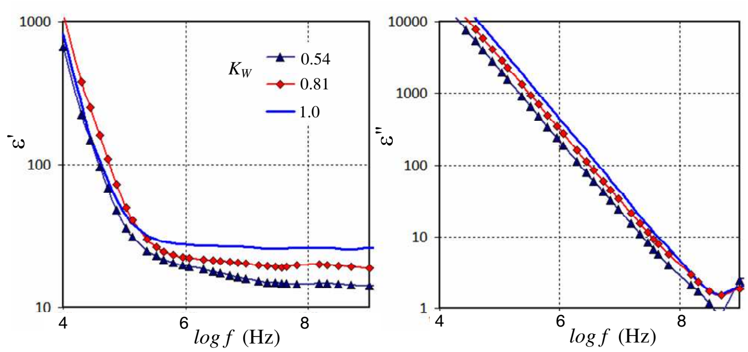


Figure 4: Dielectric permittivity ε' and ε'' of the sample No. 4, saturated with deionized water at different K_W.

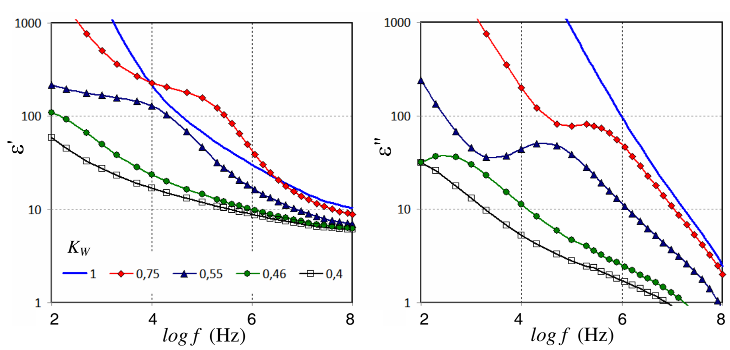


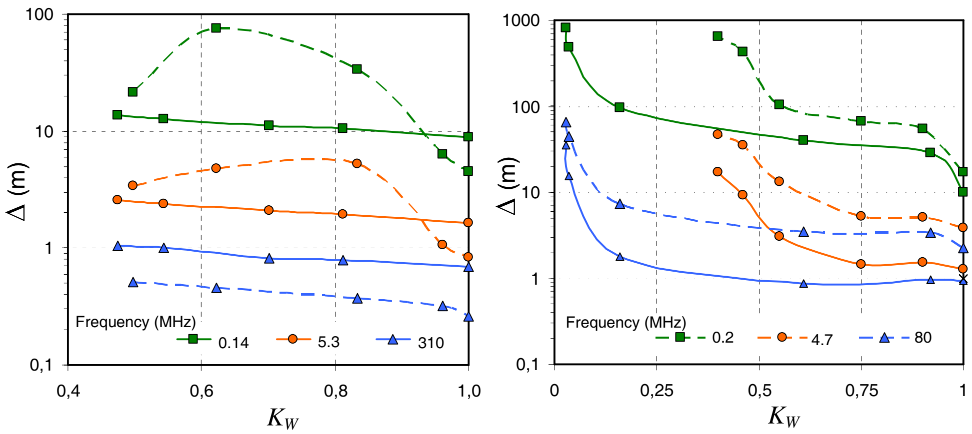
Figure 5: Dielectric permittivity ε' and ε'' of the sample No. 6, saturated with deionized water at different K_W.

with the increasing of the water saturation level.

The skin layer thickness was determined by the following formula:

$$\Delta = \frac{\lambda_0}{2\pi\kappa} \tag{1}$$

where λ_0 — is a wavelength in vacuum , κ — is an imaginary part of the complex refractive index $n* = n - i\kappa = \sqrt{\varepsilon' - \varepsilon''}$.



(a) (b)

Figure 6: Skin layer thickness dependence on water saturation level at different frequencies. (a) Quartz granules, No. 2 is shaped lines, No. 4 is continuous lines; (b) solid sandstones, No. 6 is shaped lines, No. 5 is continuous lines.

The skin layer thickness is much bigger in the solid sandstones due to the less porosity and less water content. The maximum of the values are in the sample No. 5 at $K_W = 0.9$–0.95 because of the dielectric relaxation.

ACKNOWLEDGMENT

This research was supported by the Russian Foundation for Basic Research, project 14-05-00151.

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