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INVESTIGATION OF DIELECTRIC SPECTRA FROM MOIST SOILS DURING FREEZING–THAWING PROCESSES

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A frequency spectrum of the complex dielectric permittivity of soils is measured in the range of frequencies from 0.5 to 15.0 GHz in the course of frost penetration and thawing. The phase transitions taking place during frost penetration and thawing are analyzed within the concept of the generalized refractive mixing dielectric model (GRMDM). Two types of water concurrently present in the soil are identified: bound and free water. Temperature dependences of the Debye model parameters for each type of water are given, and parameters of a dielectric spectroscopic model of frozen and thawed soils are found. The hysteresis phenomenon during the phase transition of the soil moisture is investigated.

INTRODUCTION

Dielectric properties of soils have been investigated for quite a long period of time [1]. Despite this fact, there is no model of dielectric permittivity of soil taking into account all physical parameters of matter. This model should include a description of relaxational characteristics as a function of such quantities as temperature, moisture, and mineral composition. An advent of such a model of dielectric permittivity of moist soils would improve the accuracy of measuring the hydrological and physical characteristics of soils using the methods of radio sounding.

One of the models providing an adequate description of the complex dielectric permittivity (CDP) of a mixture of soil and water is the generalized refractive mixing dielectric model (GRMDM) [2, 3].

This work presents the results of investigations of temperature dependences of soils within the Pogorelka station. The purpose of the study was to investigate the effect of temperature on relaxational soil properties within the radar range. A challenging aspect is the presence of bound water (as high as 9% mass in this specimen). While currently there is no sufficiently complete description of the properties of bound water, in [2–4] it was shown that its properties are significantly different from those of ordinary or free water. For this reason, the properties of bound water as a function of temperature were given a particular attention.

Measuring the complex dielectric permittivity spectra for different moisture content values in the soil provided the GRMDM parameters as a function of temperature, which allowed us to analyze the effect of temperature on relaxational processes in a moist soil.

GENERALIZED REFRACTIVE MIXING DIELECTRIC MODEL

The refraction model within a GRMDM [3] concept describes the dependence of the complex dielectric permittivity on the external electromagnetic field frequency f and the mass content of moisture in a soil m_g and is given by

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$$\frac{n_s(m_g,f,t)-1}{\rho_d(m_g)}=\begin{cases}\frac{n_m-1}{\rho_m}+\frac{(n_b(f,t)-1)}{\rho_b}m_g, & 0\le m_g\le m_{gt},\\ \frac{n_m-1}{\rho_m}+\frac{(n_b(f,t)-1)}{\rho_b}m_{gt}+\frac{(n_u(f,t)-1)}{\rho_u}(m_g-m_{gt}), \\ m_{gt}\le m_g; \end{cases} \tag{1}$$

$$\frac{\kappa_s(m_g,f,t)-1}{\rho_d(m_g)}=\begin{cases}\frac{\kappa_m}{\rho_m}+\frac{\kappa_b(f,t)}{\rho_b}m_g, & 0\le m_g\le m_{gt},\\ \frac{\kappa_m}{\rho_m}+\frac{\kappa_b(f,t)}{\rho_b}m_{gt}+\frac{\kappa_u(f,t)}{\rho_u}(m_g-m_{gt}), \\ m_{gt}\le m_g, \end{cases} \tag{2}$$

where $n_{s,m,u,b}$ and $\kappa_{s,m,u,b}$ are the refraction coefficient and the normalized absorption coefficient, with the subscripts *s*, *m*, *u*, *b* denoting characteristics of mixture, mineral, free and bound water, respectively, which are related to the real and imaginary parts of CDP as follows:

$$n_{s,m,u,b}=\tfrac{1}{\sqrt{2}}\sqrt{\sqrt{\varepsilon'^2_{s,m,u,b}+\varepsilon''^2_{s,m,u,b}}+\varepsilon'_{s,m,u,b}}\ ; \tag{3}$$

$$\kappa_{s,m,u,b}=\tfrac{1}{\sqrt{2}}\sqrt{\sqrt{\varepsilon'^2_{s,m,u,b}+\varepsilon''^2_{s,m,u,b}}-\varepsilon'_{s,m,u,b}}\ , \tag{4}$$

m_{gt} is the limiting content of bound moisture in this type of soil, $\rho_{d,m,u,b}$ are the densities of a dry mixture, monolith, and free and bound water, respectively. The dielectric properties of the bound and free water are well described by the Debye formula

$$\varepsilon_{b,u}=\varepsilon_\infty+\frac{\varepsilon_{sb,u}-\varepsilon_\infty}{1-i2\pi f\tau_{b,u}}+i\frac{\sigma_{b,u}}{2\pi f\varepsilon_0}\ , \tag{5}$$

where ε_∞ is the "optical" dielectric permittivity controlled by the atomic and electronic polarizations independent of the signal frequency *f*, $\varepsilon_{sb,u}$ is the "static" dielectric permittivity, $\tau_{b,u}$ is the effective relaxation time of molecules, $\sigma_{b,u}$ is the ionic conductivity of a water solution, and $\varepsilon_0=8.854\cdot10^{-12}$ F/m is the dielectric permittivity of vacuum. The subscripts *u* and *b* refer to the characteristics of free and bound water.

MEASUREMENT PROCEDURE

In order to measure the CDP spectrum of a soil, use was made of an experimental setup described in [5]. A soil specimen was placed into a container representing a section of coaxial cable waveguide with the specimen under study serving as a dielectric filling. The coaxial cable dimensions ensure a single-mode regime, that is provide for propagation of the main type TEM and suppression of higher harmonics. The container is switched to a Rohde-Schwarz ZVK vector analyzer. This vector analyzer provides for the frequency spectrum measurements of the elements of the scattering

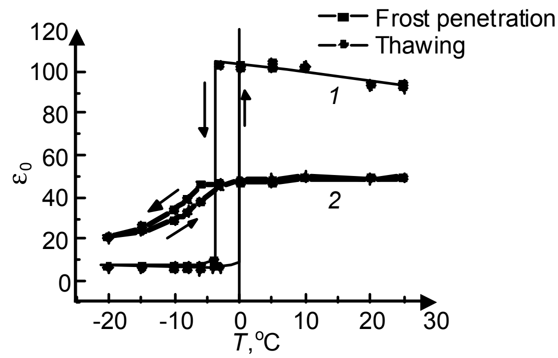

Fig. 1. Static dielectric permittivity of free (curve *1*) and bound (curve *2*) water.

matrix of a switched device within a wide frequency range. The prescribed temperature range is maintained by an SU-241 Espec temperature chamber. The complex dielectric permittivity is calculated using the formula reported in [5]. Before the measurements, a calibration procedure is performed in order to take into account the effect of transitional elements in the measurement system.

The measurements of the CDP spectrum were made within the range of frequencies from 0.5 to 15.0 GHz in a soil sample with different moisture content within the temperature range from +25 to –20°C, after which the sample underwent thawing to the initial temperature. Distilled water was used for wetting the sample.

To interpret the data obtained and to present the temperature effect on the relaxational processes in the soil, the GRMDM parameters were found using a procedure reported in [3, 5].

RESULTS AND DISCUSSION

The CDP spectra from the soils sampled in the Pogorelka test-field were measured within the frequency range from 0.5 to 15.0 GHz and for different moisture content in the course of freezing – thawing process. These CDP spectra were used to obtain the GRMDM parameters as a function of temperature. The maximum content of bound water was found to be 0.09 g/g. The spectroscopic parameters of the mineral were taken to be constant due to their negligible dependence on temperature: $\frac{n_m - 1}{\rho_m} = 0.39$, $\frac{\kappa_m}{\rho_m} = 0$. The optical dielectric permittivity for both types of water was assumed to be 4.9. The effect of temperature on density of bound and free water was disregarded in view of limitations of the calculation procedure for the GRMDM parameters; the values therefore remained to be equal to unity. Shown in Fig. 1 is the temperature dependence of static DP for the case of free and bound water.

It is evident from the figure that there is no marked phase transition in the case of bound water, while in the case of free water there is a pronounced phase transition corresponding to crystallization of water and formation of ice. A conclusion could be drawn that within the temperature interval under study bound water does not freeze and the phase transition is smeared over a wide temperature region. Note should also be made of a hysteresis in the curve for the static DP of free water, which could be attribute to a well-known phenomenon of water supercooling [6]. A similar hysteresis is also observed for bound water. The electrostatic forces acting on bound water molecules retard the formation of an ice crystal; nevertheless, this result could be interpreted as transition of water in the course of cooling into a certain intermediate structural state between the solid and liquid phases, wherein the bonds are being rearranged while the ice structure is not completely formed as would be the case for free water [7, 8].

Figures 2 and 3 depict the temperature dependences for the relaxation time and conductivities of free and bound water, respectively. While analyzing these curves, no conspicuous differences were found in these values between the freezing and thawing stages. A decrease in the relaxation time and an increase in conductivity with temperature are quite noticeable, which is in conformity with the fundamental concepts of the physics of dielectrics [9].

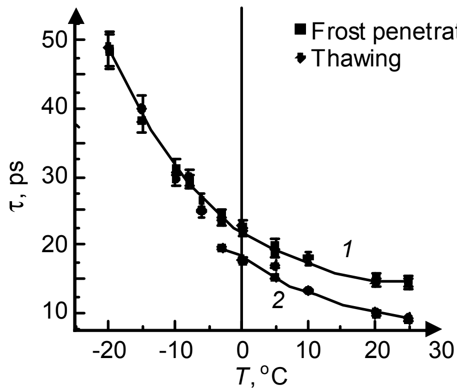

Fig. 2

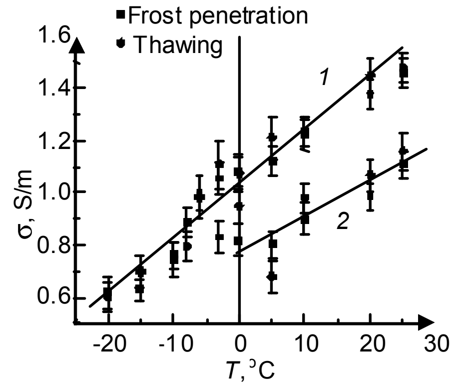

Fig. 3

Fig. 2. Relaxation time of bound (curve *1*) and free (curve *2*) water.

Fig. 3. Conductivity of bound (curve 1) and free (curve 2) water.

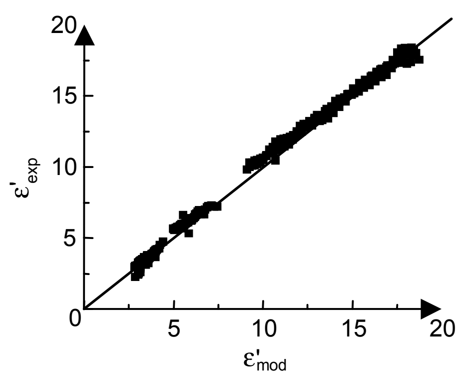

Fig. 4

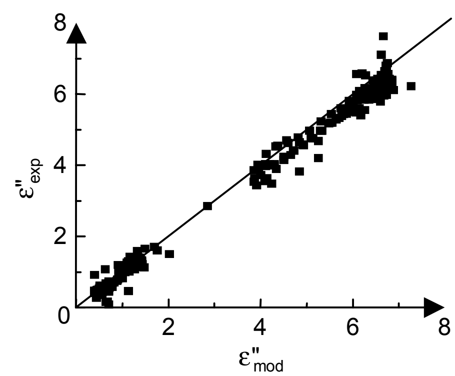

Fig. 5

Fig. 4. Comparison of the measured and model values of ε' for the temperatures + 10 and –10°C.

Fig. 5. Comparison of the measured and model values of ε" for the temperatures + 10 and –10°C.

To simplify interpretation and to avoid certain technical difficulties, no analysis of water bound on the surface of ice was performed; it was therefore assumed that at the temperature –4°C all free water was transformed into ice. The values of the parameters of free water are not shown at the temperatures where water is in the frozen state, as there are no relaxational processes in ice within the range of frequencies in question, and CDP of ice can be assumed to be constant and equal to $\varepsilon^{*}_{\rm ice} = \varepsilon_\infty \approx 3.15$ [10]. Considerable differences in the relaxation parameters for bound and free water imply that these types of water differ in their physical properties.

Figures 4 and 5 show the dependences of the experimentally measured imaginary and real parts of CDP of soil on the model values for the spectral range under study and the temperatures +10 and –10°C. The analysis was performed for two soil samples: 1) moisture content m_g = 0.34 g/g and dry mixing density ρ_d = 1.59 g/cm^3 and 2) moisture content m_g = 0.09 g/g and dry mixing density ρ_d = 1.17 g/cm^3. The first sample is characterized by a high value of saturation and the second sample is characterized by a limiting content of bound water. The model values were calculated by the formulas $\varepsilon'_{\text{mod}} = n_s^2 - \kappa_s^2$ and $\varepsilon''_{\text{mod}} = 2n_s\kappa_s$ using Eqs. (1)–(5) and the results obtained for the spectroscopic parameters shown in Figs. 1–3. The data included correspond both to the freezing and thawing cycles.

The graphs imply that the model used provides a good description of the experimental data.

SUMMARY

Thus, in this work we have measured the CDP spectrum of soils sampled in the Pogorelka test-field located near the town of Krasnoyarsk. The measurements were carried out within the frequency range from 0.5 to 15 GHz and the temperature interval in the course of freezing from +25 to –20°C and in the course of thawing from –20 to +25°C. This interval includes the temperatures characteristic for the natural environment of the test-field; also it is this temperature range where major physical processes occur, which are associated with the phase transitions of water in the soil during frost penetration and thawing. We have obtained the parameters of the generalized refractive mixing dielectric model of a as a function of temperature. The results of our investigations have shown a different temperature influence on the relaxational characteristics of bound and free water in the range.

The refraction model parameters bear a clear physical meaning, which allows one to make judgments about the real pattern of relaxational processes and their dependence on temperature.

The results obtained can be extended to apply to any type of soil, since the CDP model used is a physical model, i.e., it includes the physical parameters describing the relaxational processes in matter and, unlike empirical models, is universal.

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