BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 64 (68), Numărul 1, 2018
Secţia
MATEMATICĂ. MECANICĂ TEORETICĂ. FIZICĂ

LABORATORY MEASUREMENTS FOR THE CHARACTERIZATION OF THE PHYSICAL PARAMETERS OF GEOMATERIALS AND PLANETARY ANALOGUES

BY

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Received: January 29, 2018
Accepted for publication: February 27, 2018

Abstract. Ice can be found in our Solar System, from the presence of ice water on Mars at the poles, water vapor in the atmosphere to ice-covered moons and icy crust composed of H_2O found on the moons of Jupiter and Saturn. Sea ice is frozen sea water that floats on the ocean surface. This paper presents the results of an experimental work concerning the electric properties of sea ice samples. The objectives were to determine the electric properties of the sea ice samples and to investigate how these properties vary in function of temperature and frequency. The sea ice samples were analyzed using a vector network analyzer connected to a three-wire open transmission line immersed in the saline solution. For sea ice sample a large variation of the real part of permittivity with temperature around the eutectic point was observed.

Keywords: sea ice; transmission line; permittivity; conductivity.

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1. Introduction

Sea ice is a thin and solid layer that forms by the freezing of surface seawater and is characterized by a multiphase structure that includes ice crystals as well as gas, liquid brines, solid salts and other impurities (Thomas and Diekmann, 2009). At low temperatures, sea ice forms on the ocean's surface, starting as a thin sheet of crystals that grow into a salty ice. Salt particles called brines are trapped in the ice crystals as they freeze. When no water turbulences are present, their growth is regular and a uniform columnar ice type is formed with the c-axis of the crystals aligned in the horizontal plane. In such a structure, brine inclusions can potentially migrate downwards along vertically oriented channels whose shape is governed by the temperature (Reid *et al.*, 2006). Sea ice has a bright surface that reflects sunlight back into space. Because the areas covered by sea ice absorb little solar energy, the temperatures in the polar regions are relatively cool.

If the physical properties of the fresh-water ice, are well known, the sea ice is a relatively complex substance and its properties are still under study. The transformation to a completely solid mixture of pure ice and solid salts is attained only at very low temperatures, so extreme that they are rarely encountered in nature. The physical properties of sea ice depend strongly on salinity, temperature and age (Schwerdtfecer, 1963).

The salinity of sea ice is governed by both age and location. For example, because of its rapid formation Antarctic first year sea ice contains more brine trapped in its granular structure, and remains quite saline with time (Mattei *et al.*, 2017).

Global warming still affects sea ice formation because when the increasingly warming temperatures melt sea ice, less bright surfaces are available to reflect sunlight back into space. The Solar energy is absorbed at the surface, and temperatures increase further (Weeks, 2010).

The study of Arctic sea ice has recently gathered importance for both climate change monitoring (Vinnikov *et al.*, 1999; Vihma, 2014) and possible trans-Arctic trade shipping along the Northwest Passage (Ho, 2010).

In the present study, we focus on the electric and magnetic properties of the sea ice samples and how these properties vary in function of temperature and frequency.

2. Experimental Details

The sea ice sample was prepared by dissolving approximately 55.55 grams of sodium chloride in 1.8 liters of water. Estimation of electromagnetic properties was done according to temperature (from liquid to solid state) using a vector network analyzer connected to a tri-wire open transmission line immersed in the saline solution. To carry out measurements as a function of temperature, the sample was inserted into a climatic chamber where a 200 K temperature is reached.

The experimental device presented in Fig. 1 is divided into three parts: the climatic chamber where the sea ice sample is formed, the network analyzer vector where the collected data from the sample are recorded and the computer.

The already prepared saline solution of 35 grams/liter was introduced in the climatic chamber at a temperature of -75°C.

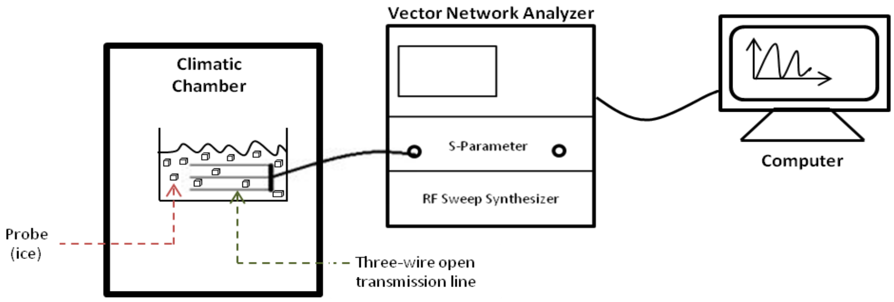

Fig. 1 – Scheme of the experimental setup.

To measure the electrical properties ($\varepsilon_r^{'}, \varepsilon^{''} = \sigma/\omega\varepsilon_0$) of a non-magnetic medium ($\mu_r = 1$) we used a transmission line that is filled with the material to be analyzed and terminates with an infinite impedance (transmission line open at its termination). Because $Z_{L\to\infty}$ the input admittance Y_{in} of the probe is described by Eq. (1):

$$Y_{in} = \frac{1}{Z_{cable}} \frac{1-S_{11}}{1+S_{11}} = iY_c \tan(kl) = iY_{c0}\sqrt{\varepsilon_r^{'} - i\sigma/\omega\varepsilon_0} \tan(\frac{\omega}{c}\sqrt{\varepsilon_r^{'} - i\sigma/\omega\varepsilon_0 l}) \quad (1)$$

where Z_{cable} = 50 Ω is the cable impedance, Y_c is the characteristic admittance of the line in the absence of material, c is the speed of light in vacuum and l is the length of the line.

At low frequency ($kl = \frac{\omega}{c}\sqrt{\varepsilon_r^{'} - i\sigma/\omega\varepsilon_0 l} \to 0$), the input admittance can be approximated as follows, Eq. (2):

$$Y_{in} \cong iY_{c0}\frac{\omega}{c} l\left(\varepsilon_r^{'} - i\frac{\sigma}{\omega\varepsilon_0}\right) = i\omega C_{lf}\left(\varepsilon_r^{'} - i\frac{\sigma}{\omega\varepsilon_0}\right), \omega \to 0 \quad (2)$$

where $C_{lf} = Y_{c0}l/c$ is the low-frequency line capacity that can be estimated by calibration measurements.

Electrical conductivity was calculated from the real part of the admittance which depends on the scattering parameter S_{11}, Eq. (3).

$$\sigma = \frac{\varepsilon_0}{C_{lf}} Re\{Y_{in}\} = \frac{\varepsilon_0}{Z_{cable}\ C_{lf}} Re\left\{\frac{1-S_{11}}{1+S_{11}}\right\} \quad (3)$$

The real part of permittivity is given by, Eq. (4):

$$\varepsilon_r' = \frac{1}{\omega C_{lf}} Im\{Y_{in}\} = \frac{1}{Z_{cable}\ \omega C_{lf}} Im\left\{\frac{1-S_{11}}{1+S_{11}}\right\} \quad (4)$$

At high frequencies ($\vartheta \gg \frac{\sigma}{2\pi\varepsilon_0\varepsilon_r}$) where $\frac{\omega}{c} Re\{\sqrt{\varepsilon_r}\} l = \pi/2$, the imaginary part of admittance tends to diverge and the real part has the maximum.

This allows the estimation of the real part and the imaginary part of the permittivity at frequencies ϑ_m for which $\frac{2\pi}{c}\vartheta_m\sqrt{\varepsilon_r' l} \cong (2m-1)\,\pi/2$:

$$\varepsilon_r'(\vartheta_m) = \left(\frac{c}{2\pi\vartheta_m l}\right)^2 \left\{\left[\frac{\pi}{2}(2m+1)\right]^2 - \left[\operatorname{arcoth}\left(\frac{1}{2m+1}\frac{4\vartheta_m l}{c} Re\left\{\frac{Y_{in}(\vartheta_m)}{Y_{c0}}\right\}\right)\right]^2\right\} \cong \left[(2m+1)\frac{c}{4\vartheta_m l}\right]^2 \quad (5)$$

$$\varepsilon_r''(2m+1)\pi\left(\frac{c}{2\pi\vartheta_m l}\right)^2 \operatorname{arcoth}\left(\frac{1}{2m+1}\frac{4\vartheta_m l}{c} Re\left\{\frac{Y_{in}(\vartheta_m)}{Y_{c0}}\right\}\right) \quad (6)$$

$$\sigma(\vartheta_m) = \omega_m \varepsilon_0 \varepsilon_r''(\vartheta_m) \quad (7)$$

To study the electromagnetic properties of the sample, it was necessary to estimate the geometric factors of the transmission line (C_{lf} 0 Y_{c0} e l); Knowing these parameters, we were able to evaluate the real part of permittivity and conductivity at low frequency using Eqs. (3) and (4) and the real part of permittivity and conductivity at high frequency using Eqs. (5) and (7).

The low-frequency capacity was estimated from the measurements done with the vector network analyzer on a sample of water and the conductivity measurement on the same sample made with the electrical conductivity meter by applying Eq. (3). Using the same data, the line length l could be calculated using Eq. (5) in its approximate form considering that the real part of the permittivity is $\varepsilon_r' = 87.9 - 0.4T + 9.5x10^{-4}T^2 - 1.3x10^{-6}T^3$ (T is the temperature in Celsius degrees).

3. Results and Discussion

To obtain the dielectric properties of the sample, we plotted both the real part of the permittivity (Fig. 2) and the conductivity (Fig. 3) with temperature. The real part of the permittivity for 4 different frequencies was recorded. From these graphs one can observed that the temperature at which the sample begins to melt is 252 K. Below this temperature, the water is frozen uniformly, and above this temperature liquid areas (brines zones) begin to appear inside the ice. Under these conditions, the instrument can measure the real part of permittivity only at low frequencies. Above the eutectic temperature, the high frequency estimate of $\varepsilon_r^{'}$ and σ can not be performed because the medium is too attenuating.

As a function of temperature, a large variation of the real part around the eutectic temperature is observed. Fig. 2 also shows that the real part of permittivity is higher for the lowest frequency. Electrical properties are very sensitive to the physical state of the sample.

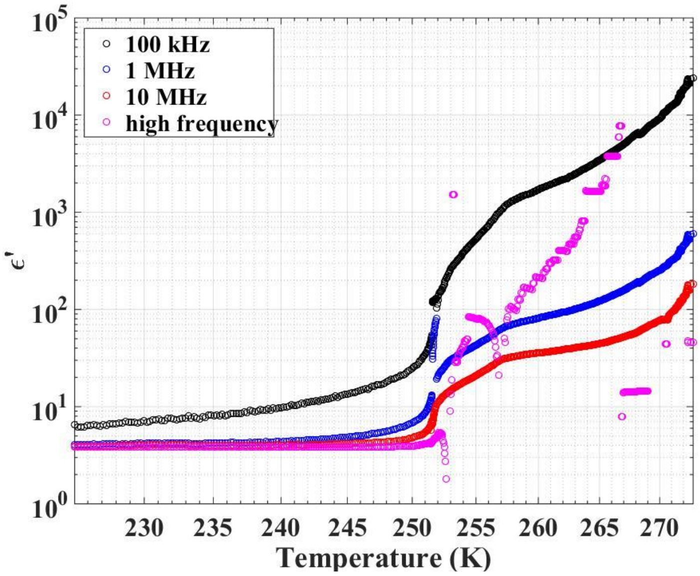

Fig. 2 – The real part of the permittivity as a function of temperature.

A greater variation of the conductivity versus the variation of the real part of the permittivity is observed around the eutectic temperature. This is due to the fact that conductivity is a physical parameter that generally varies greatly. When the temperature is high, the conductivity is due to the conductivity of the brines. Similar results have been obtained by (Moore *et al*., 1994). In this study the conductivity values varied between 10^3 to 10^4 μS/m, as the frequency was changed from several kHz up to a few MHz on both synthetic and natural sea ice grown under different conditions.

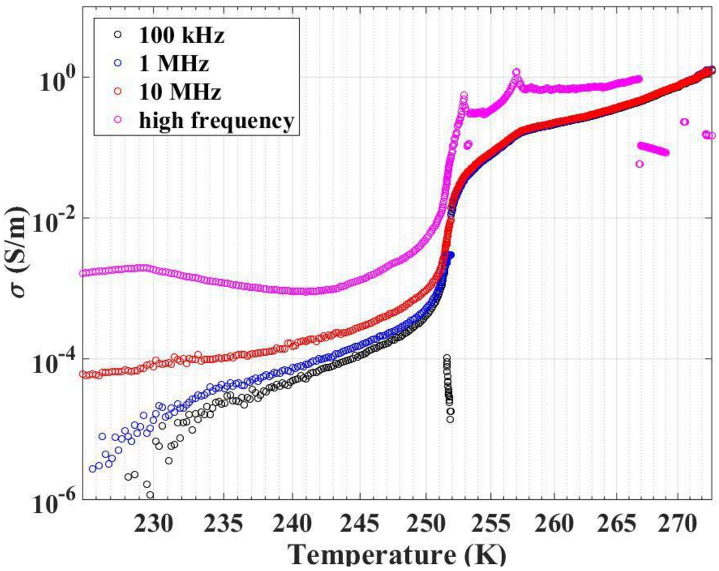

Fig. 3 – Conductivity as a function of temperature.

In liquid phase, the conductivity of the sample does not depend on the frequency. When the sample passes in a solid state, we observe a small dependence with the frequency as a response of charges produced by the self-dissociation of H_2O molecules (Artemov and Volkov, 2014).

The experimental results obtained by these experiments have permitted a better definition of the dielectric behaviour of sea ice.

3. Conclusions

The main objectives of this work were to determine the electromagnetic properties (permittivity and conductivity) of sea ice sample and to investigate how these properties vary with temperature and frequency.

For sea ice sample we observed a large variation of the real part of permittivity as a function of the temperature around the eutectic point. We also observed that the real part of permittivity increases when decreasing the frequency. The conductivity measurements showed a greater variation with temperature than the ones of the real part of the permittivity at 252 K.

The measurement of dielectric properties of ice salted water reflects the effects of environmental parameters and conditions that operate on geomaterials.

Acknowledgements. This work was financially supported by the Romanian Space Agency (ROSA) within Space Technology and Advanced Research (STAR) Program, Project number 162/20.07.2017 and 169/20.07.2017.

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MĂSURĂTORI DE LABORATOR PENTRU CARACTERIZAREA PARAMETRILOR FIZICI AI GEOMATERIALELOR ȘI AI ANALOGILOR PLANETARI

(Rezumat)

Sunt raportate rezultatele unui studiu experimental privind proprietățile electrice și magnetice ale gheții marine. Scopul acestui studiu a fost investigarea proprietăților electromagnetice ale probelor de gheață marină și modul în care aceste proprietăți variază în funcție de temperatură și frecvență. Un alt obiectiv al acestui studiu a fost acela de a observa procesele care se produc atunci când apa marină trece din stare lichidă la stare solidă și înțelegerea modului în care funcționează analizorul de rețea și camera climatică. O discuție despre variația conductivității a fost facută prin comparație cu rezultate anterioare ale altui grup de cercetare.