

Verification of dielectric constant by COMSOL Multiphysics

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Abstract — the aim of the paper is experimental measurement of the capacity and estimating relative permittivity of unknown material using laboratory measurement system and comparing results with simulation model created in COMSOL Multiphysics.

Keywords — relative permittivity, capacitance, plate capacitor COMSOL Multiphysics

I. INTRODUCTION

Dielectric constant is a ratio of the electric field strength in vacuum to the electric field strength with medium. The relative permittivity is directly related to the electronic, ionic and orientation of polarization of the material. The first two of these are induced by the applied field, and are caused by displacement of the electrons within the atom, and atoms within the molecule, respectively. The third only exists in polar materials, i.e. those with molecules having a permanent dipole moment. Electronic and ionic polarization are temperature independent, but orientation of polarization, depending on the extent to which the applied field can order the permanent dipoles against the disordering effect of the thermal energy of their environment, varies inversely with absolute temperature. All of these polarization mechanisms can only operate up to a limiting frequency, after which a further frequency increase will result in their disappearance.

The frequency at which these mechanisms drop out is related to the inertia of the moving entities involved. Typically, electronic polarization persists until a frequency of about 10¹⁶ Hz, ionic polarization until about 10¹³ Hz, while the dispersion for orientation of polarization may lie anywhere within a wide frequency range, say 10²–10¹⁰ Hz, depending on the material and its temperature. In addition to these polarization mechanisms, the existence of interfacial effects such as macroscopic discontinuities in the material, or blocking at the electrodes, causes the trapping of charge carriers, and such phenomena, as well as the inclusion in the dielectric of impurities giving rise to conducting regions, result in behavior classified under the general heading of Maxwell–Wagner effects. These give rise to an effective polarization and associated loss, the frequency behavior of which is similar to that of orientation of polarization, with a dispersion region which may lie in the region of 1 Hz or lower.

The permittivity of many substances changes not only with frequency and temperature, but also with specimen age and history. Two specimens of nominally the same material may have significantly different permittivity because of different manufacturing processes, different amounts of oxidation, and different inclusions, some of which might have been deliberately introduced, e.g. anti-oxidants. For such reasons, tables of values should be used as an indication of the magnitudes to be expected, and not as a source of precise data which can be repeated by accurate measurements on particular test specimens, except in cases in which the physical and chemical state of both the reference material and

the test specimen are very closely specified. The properties of ferroelectric materials depend on so many factors that it is inappropriate to include them in tables of data. Generally, they have permittivity of the order of a thousand, strongly dependent on applied voltage and temperature, and exhibit considerable power loss [2].

In this paper the laboratory measurement system for measuring dielectric constant is introduced. This system is in fact plate capacitor which allows to measure dielectric specimen is in form of thin sheets. Measuring of relative permittivity is made indirectly. First, the capacitance is measured a then using formula (2) the relative permittivity is obtained.

II. DIELECTRIC CONSTANT

Dielectric constant also called relative permittivity is defined as a ratio of capacity of capacitor with dielectric to capacity of vacuum capacitor or with capacitor with air gap.

$$\varepsilon_r = \frac{C_x}{C_0} \quad (1)$$

A capacitor filled with a dielectric material has a real capacitance ε_r times greater than would have a capacitor with the same electrodes in vacuum.

A. DIELECTRIC CONSTANT OF POLYPROPYLENE

In our case, as a reference specimen thin plastic sheet made of polypropylene (PP) was chosen. PP is the non-polar plastic. In this material there are no polar dipoles present and the application of an electric field does not try to align any dipoles. The electric field does, however, move the electrons slightly in the direction of the electric field to create “electron polarization”, in this case the only movement is that of electrons and this is effectively instantaneous. These materials tend to have high resistivity and low dielectric constants [3]. Typical values of dielectric constant of PP are shown in Table 1[1].

Values are given for frequencies of 1 kHz, 1 MHz, and 1 GHz; in most cases the dielectric constant at frequencies below 1 kHz does not differ significantly from the value at 1 kHz.

Since the dielectric constant of polymeric material can vary with density, degree of crystallization, and other details (e.g. frequency, temperature, age) of a particular sample as stated before, the values given here should be regarded only as typical or average values [1].

Tab. 1 Relative permittivity of polypropylene

1kHz	1MHz	1GHz	t[°C]
2.30	2.30	2.30	25.00

Next steps were determining the accuracy and error of measurement system (the reference value was relative permittivity listed in Table 1). Then the measurement of capacity of unknown material was made. Measurement of capacitance is commonly made using (1), but in our case, the measurement system does not allow to set the air gap precisely. The calculation of relative permittivity is made using following formula:

$$C = \varepsilon_r \varepsilon_0 \frac{S}{d} \quad (2)$$

Where C is capacity, ε_r is relative permittivity, ε_0 is permittivity of vacuum, S expresses the area of electrodes and d denotes the distance between the electrodes.

III. MEASUREMENT SYSTEM

The measurement system is shown in the Fig.1. It consists of two aluminum electrodes. Between the electrodes measured specimen is located. To ensure the distance between the electrodes is the same as the thickness of specimen; electrodes are set between two plates which are tightened with

four bolts. Both electrodes should be placed right opposite each other. To ensure the plates and electrodes remains in its place two pins are used.

Whole measurement system is described by following parameters. a_w is width of plate [mm], a_h is height of plate [mm], b_w is width of electrode [mm], b_h expresses the height of electrode [mm], b_t is thickness of electrode [mm], and t is thickness of specimen [mm].

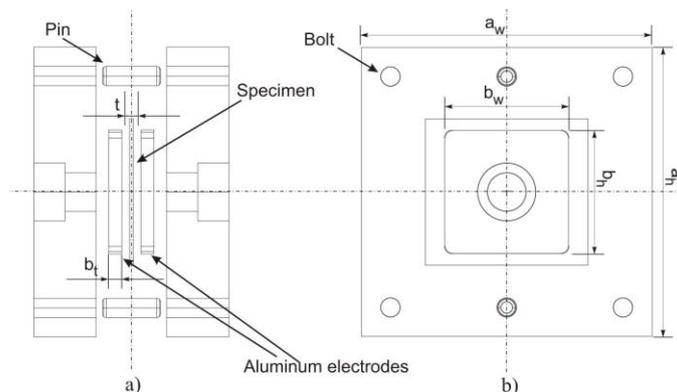


Fig. 1. Measurement system

Model of measurement system (plate capacitor) is created in COMSOL Multiphysics software in AC/DC module (Fig.2). COMSOL Multiphysics is software package that solves systems of coupled three-dimensional partial differential equations. This software can be used to model different physical phenomena including electromagnetics. It uses the finite element method of solution and can model the complex problems, geometries or material properties in 2D or 3D representation for better understanding some phenomena. This model is simplified and consists only of electrodes and specimen that are placed in air domain.

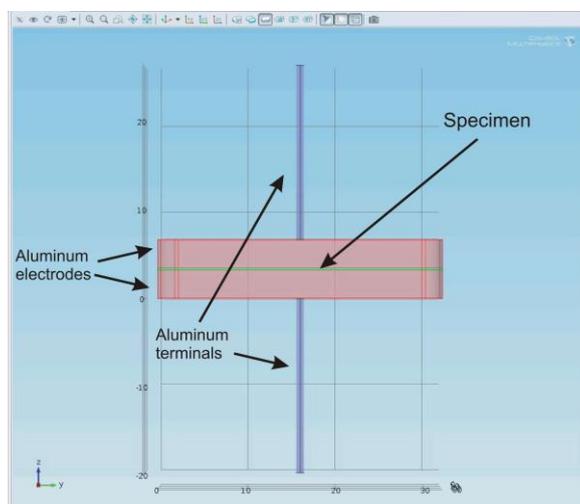


Fig. 2. Model of measurement system in COMSOL Multiphysics

IV. RESULTS

For simulation the model shown in Fig.2 was used. As the material of electrodes aluminum and as the dielectric material PP with relative permittivity $\epsilon_r = 2.3$ was selected as stated in Table 1. Problem was solved as electrostatic problem.

Very important parameter of simulation is a mesh. Proper size and shape of mesh elements influences the accuracy of solution; the finer the mesh elements, the better the solution accuracy. Of course, very fine mesh can be a problem and computer cannot solve such model. It is very important to find optimal number of elements. In our case the tetrahedral mesh of 691 737 elements was created. Parameters used in simulation:

Height of electrode/specimen: $b_h = 32\text{mm}$
Width of electrode/specimen: $b_w = 32\text{mm}$
Thickness of electrodes: $b_t = 3.3\text{mm}$
Thickness of specimen: $t = 0.1\text{mm}$
Radius of round corners: $r = 2\text{mm}$
Area of electrodes/specimen: $S = 1020.57\text{mm}^2$
Physics: electrostatics
Relative permittivity (PP): $\epsilon_r = 2.3$
Number of mesh elements: 691 737
Applied voltage: $V_0 = 1\text{V}$

The simulation results are shown in Fig.3. The simulation took 48s and capacitance calculated by software is $C_{simPP} = 210.6\text{ pF}$. The capacitance using (2) is $C_{calcPP} = 207.8\text{ pF}$.

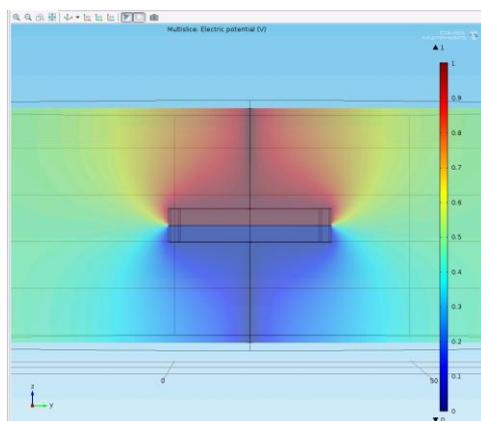


Fig. 3. Electric potential

The measurement system is depicted in Fig.4 and measurements were made using LCR bridge Hameg HM8118 with basic accuracy 0.05% (Fig.5). The thickness of used PP sheet was 0.05mm and in measurement two pieces of specimen were used.

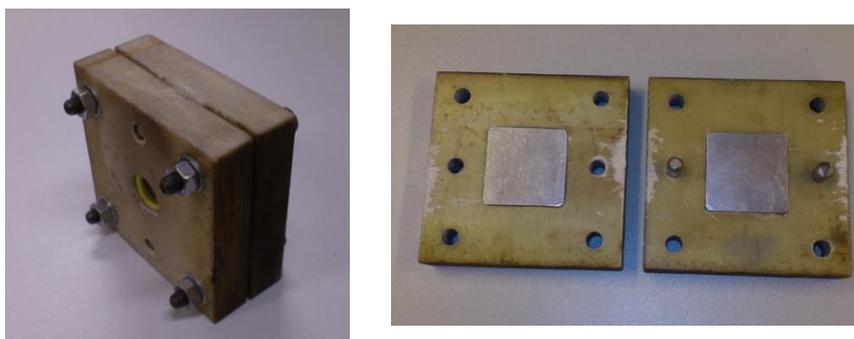


Fig. 4. Measurement system



Fig. 5. LCR measurement bridge HM8118

For better accuracy 10 measurements were taken, always with new specimen. The measurement was made at 20Hz and 60Hz. The values of obtained capacitance in [F] are listed in Table 2.

Tab. 2 Capacitor with PP dielectric

	20Hz	60Hz	t[°C]
1.	1.94E-10	1.93E-10	20
2.	1.90E-10	1.89E-10	20
3.	1.94E-10	1.92E-10	20
4.	1.90E-10	1.89E-10	20
5.	1.91E-10	1.90E-10	20
6.	1.90E-10	1.88E-10	20
7.	1.91E-10	1.90E-10	20
8.	1.90E-10	1.89E-10	20
9.	1.90E-10	1.90E-10	20
10.	1.90E-10	1.90E-10	20
Average:	1.91E-10	1.9E-10	

Relative permittivity of PP for every measurement is then calculated using (2) and shown in Table 3. Average value of permittivity of measured PP specimen at 20 Hz is $\epsilon_r=2.114$.

Tab. 3 Relative permittivity of PP

	20[Hz]	60[Hz]
1.	2.141	2.131
2.	2.106	2.095
3.	2.144	2.128
4.	2.105	2.093
5.	2.116	2.103
6.	2.097	2.075
7.	2.114	2.100
8.	2.105	2.090
9.	2.106	2.103
10.	2.105	2.103
Average:	2.114	2.102

The thickness of used specimen was 0,155 mm. Again, 10 measurements were taken, always with new specimen at frequencies 20Hz and 60Hz. The values of obtained capacitance in [F] are listed in Table 4.

Tab. 4 Capacitor with unknown dielectric

	20	60	t[°C]
1.	1.75E-10	1.73E-10	20
2.	1.74E-10	1.73E-10	20
3.	1.73E-10	1.72E-10	20
4.	1.84E-10	1.81E-10	20
5.	1.84E-10	1.82E-10	20
6.	1.73E-10	1.71E-10	20
7.	1.74E-10	1.72E-10	20
8.	1.78E-10	1.76E-10	20
9.	1.76E-10	1.74E-10	20
10.	1.72E-10	1.71E-10	20
Average:	1.76E-10	1.74E-10	

Relative permittivity of unknown material for measured capacitance is shown in Table 5.

Tab. 5 Capacitor with unknown dielectric

	20[Hz]	60[Hz]
1.	2.995	2.971
2.	2.987	2.961
3.	2.974	2.943
4.	3.153	3.110
5.	3.151	3.120
6.	2.967	2.940
7.	2.981	2.954
8.	3.057	3.021
9.	3.015	2.985
10.	2.954	2.925
Average:	3.023	2.993

For simulation model of capacitor filled with unknown dielectric the model depicted in Fig.2 was used. The parameters of the model remain the same, except for the parameters listed below:

Thickness of specimen: $t = 0.155\text{mm}$
 Relative permittivity: $\epsilon_r = 3.023$
 Number of mesh elements: 756 399

For the value of relative permittivity of dielectric material used in simulation the average value at 20Hz was set. The capacitance calculated by software is $C_{simU} = 178.6\text{pF}$.

In the Table 6 the results of analytic, simulation and experimental method are summarized. Measured permittivity is used in analytic and simulation approach and compared with experimental measurement.

Tab. 6 Parameters used in simulation for unknown specimen

	Analytic	Simulation (Electrostatics)	Measurement Average (20Hz)
PP	1.91E-10	1.94E-10	1.91E-10
$\epsilon_r = 2.114$			
Unknown	1.76E-10	1.79E-10	1.76E-10
$\epsilon_r = 3.023$			

The experimental results show that relative permittivity of PP differs (8.1%) from permittivity stated in literature. This can be caused by various factors including temperature, frequency, density or age of particular specimen. There are other factors which can also influence the accuracy of measurement, e.g. accuracy of LCR Bridge or accuracy during fabrication of measurement system (poor contact of electrodes or electrodes can be slightly shifted from each other causing lesser contact area). We can assume that the average value of relative permittivity (in this case) and the capacity of capacitor filled with this unknown material may differ from real value with relative deviation of 8,1%.

V. CONCLUSION

In this paper the measurement and calculation of relative permittivity was presented. For our purpose the measurement system that consists of two aluminum electrodes was built. Between electrodes the dielectric specimen was placed. This system represents the plate capacitor which capacity can be easily calculated whether analytic or simulation method. The simulation of plate capacitor was made using COMSOL Multiphysics software which solved the electric fields and calculated the capacitance of such capacitor. First, the measurement of relative permittivity for known material – polypropylene was made. Then the measurement of capacity of unknown material and calculation of relative permittivity was made. In simulation model the average values from both

measurements were used for comparison results with experimental approach. This system allows measuring of capacitance of plate capacitor filled with thin dielectric sheet with good accuracy. Together with finite elements method of solution this system can be used in educational process for students to better understand the phenomenon of electromagnetism and for practical experiments.

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