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ELECTRICAL PROPERTIES OF POPCORN GRAINS

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This work contains the results of measuring the electrical properties of popcorn grains. Interest in electrical properties of biological materials resulted in engineering research in this field. The results of measurements are used for determining the moisture content, the surface level of liquid and grainy materials, for controlling the presence of pests in grain storage, for a quantitative determination of mechanical damage, in applications of dielectric heating, and in many other cases. Electrical measurements on these materials are of fundamental importance in relation to the analysis of quantity of absorbed water and dielectric heating characteristics. It is a well-known fact that electrical properties of materials, namely dielectric constant and conductivity, are affected by the moisture content of material. This fact is important for the design of many commercial moisture-testing instruments for agricultural products. The knowledge of dielectric properties of materials is necessary for the application of dielectric heating. The aim of this work was to perform the measurements of conductivity, dielectric constant and loss tangent on samples of popcorn grains, the electrical properties of which had not been sufficiently measured. Measurements were performed under variable moisture content and the frequency of electric field in the range from 1 MHz to 16 MHz, using a Q meter with a coaxial probe. It was concluded that conductivity, dielectric constant and loss tangent increased with increase of moisture content, and dielectric constant and loss factor decreased as the frequency of electric field increased.

Keywords: complex electrical permittivity, dielectric constant, conductivity, popcorn

Interest in electrical properties of biological materials resulted in engineering research in the field of agriculture last years. The knowledge of physical properties of agricultural products is useful, if not essential, in the design of any agricultural machine. The investigation and determination of physical properties of agricultural materials has also resulted in the development of many instruments. The study of electrical properties is important for predicting the behaviour of materials in electric field or for knowing how the presence of material can influence the field or an associated electrical circuit. Electrical measurements on these materials are of fundamental importance in relation to the analysis of quantity of absorbed water and dielectric heating characteristics. Dielectric properties of materials represent an important part of electrical properties. The research of electrical properties is finding utilisation in a lot of technical applications. Results of measurements are used for determining the moisture content, the surface level of liquid and grainy materials, for controlling the presence of pests in grain storage, for the quantitative determination of mechanical damage, and in many other cases (Hlaváčová, 1999). Electrical properties of many biological materials have already been investigated. It was discovered that electric properties of these materials are very affected by the moisture content of material. Small quantities of adsorbed water can cause large changes in electrical properties of hygroscopic materials. An extensive review of the literature on dielectric properties of agricultural materials was published (Nelson, 2007) and includes a number of potential applications in which dielectric properties of such products are of interest. Electrical properties of grains and seeds depend on their moisture content and on the frequency of electric field. Dielectric properties of grains and seeds have been explored in certain frequency ranges, where these

properties were important for dielectric heating applications or of interest for moisture measurement or detection for process control (You and Nelson, 1988). Dielectric properties of most biological materials vary with frequency and temperature. They are also highly dependent upon moisture content in hygroscopic materials. Some aspects of the nature of frequency dependence of dielectric properties have been included in the published review (Nelson et al., 2007). A study of the frequency dependence of dielectric properties of insects and grain has also been reported for the range from 250 Hz to 12 GHz (Nelson et al., 2007). In that study, the range from 10 MHz to 100 MHz was identified as the most promising frequency range for selectively heating rice weevils in wheat through differential energy absorption from alternating electric field. For a more complete picture, however, similar data are needed for the temperature dependence of dielectric properties. With recent advances in the practical application of microwave heating, there has developed a need for information on dielectric properties of materials to which such energy is applied. While some information is available on dielectric properties of grains and seeds at lower frequencies (Nelson et al., 2007; You and Nelson, 1988; Lawrence et al., 1990), there is a lack of information on these properties at microwave frequencies. Therefore, dielectric properties of several kinds of grains and seeds have been measured at a few various microwave frequencies, and dependence on moisture content has been considered. Nelson (1991) gave a comprehensive summary of dielectric methods for measuring the moisture present in materials. Nelson (1999) discussed some methods of measuring the moisture content of soil. One of these methods is a dielectric method. Resultant accuracy and temperature effects were also noted by Nelson (1999). Interest in the dielectric behaviour of biological materials

increased with the advent of radio frequency heating techniques. Lawrence et al. (1992) discussed in detail the application of radio frequency heating to good electrical conductors as well as poor electrical conductors. You and Nelson (1988) conducted a study of the dielectric constant of rice grains. They measured the dielectric constant and loss factor at frequencies from 435 Hz to 1,740 Hz and found that the dielectric constant of rice grains depended on density, moisture content, temperature and frequency. This investigation gave base for the design of many instruments and application of dielectric heating to agricultural products.

Material and methods

Every material influences the electric field to which it is subjected. The relation between parameters of electromagnetic field and properties of material medium is described with the permittivity ϵ and permeability μ of this medium. Both parameters describe electromagnetic properties of matter. Permittivity is a complex quantity:

$$\epsilon^* = \epsilon' - j\epsilon'' \quad (1)$$

The real part of complex permittivity ϵ^* is the permittivity of dielectric ϵ . The coefficient of imaginary part ϵ'' characterises losses in dielectric. Dielectric properties of materials are generally formulated by relative complex permittivity:

$$\epsilon_r^* = \frac{\epsilon^*}{\epsilon_0} = \frac{\epsilon'}{\epsilon_0} - j\frac{\epsilon''}{\epsilon_0} = \epsilon_r' - j\epsilon_r'' = \epsilon_r'(1 - \tan \delta) \quad (2)$$

where:

$$\tan \delta = \frac{\epsilon_r''}{\epsilon_r'} = \frac{\epsilon''}{\epsilon'} = \frac{\sigma}{\omega\epsilon'} \quad (3)$$

is the loss tangent of loss angle $\frac{\pi}{2}$; it is the angle completing to the phase difference between voltage and current flowing through the dielectric; ϵ_0 is vacuum permittivity ($8.854 \times 10^{-12} \text{ F.m}^{-1}$). To measure the dielectric properties of samples of seeds, a resonant method has been used. This method for measuring the dielectric properties of seeds and liquids in a frequency range from 100 kHz to 300 kHz was developed by Nelson et al. (2007). The capacitance of the testing capacitor was measured by the Q meter TESLA MB 560. By measuring the permittivity ϵ' and loss tangent $\tan \delta$ of the testing capacitor, the real capacitor can be considered as a lossless capacitor connected with active resistance in a parallel or serial configuration. The substance of measurement is to determine the magnitude of capacitance and resistance of parallel or serial configuration of dielectric at a specific frequency. The Q meter was connected with the testing coaxial capacitor, which was used as a sample holder. The measurement was performed in a frequency range from 1 MHz to 16 MHz. Dielectric constant ϵ_r was calculated according to the following relations:

$$\epsilon_r = \frac{C - C_x}{C_0} \quad (4)$$

$$C = C_1 - C_2 \quad (5)$$

where:

- C – capacitance of testing capacitor with a sample, F
- C_0 – capacitance of empty testing capacitor free of interconnector capacitance, F
- C_x – capacitance of interconnector, F
- C_1 – capacitance of tuning capacitor by resonance and by no connection of testing capacitor, F
- C_2 – capacitance of tuning capacitor by resonance and by connection of testing capacitor, F

The resistance R of the testing capacitor was measured using a multimeter MASTER M830BUZ. Sample conductivity σ was determined according to the following relation:

$$\sigma = \frac{\ln \frac{r_1}{r_2}}{2\pi l R} \quad (6)$$

where:

- r_1 – radius of outer electrode, 0.033 m
- r_2 – radius of inner electrode, 0.008 m
- l – length of capacitor, 0.06 m

Loss tangent $\tan \delta$ can be computed using the following relations:

$$\tan \delta = \frac{1}{\omega R C} = \frac{\sigma}{\omega\epsilon} \quad (7)$$

$$\omega = 2\pi f \quad (8)$$

where:

- f – frequency of electric field, Hz
- ϵ – sample permittivity, F.m^{-1}

The effect of moisture content on dielectric constant and loss factor in frequency range from 1 MHz up to 16 MHz and the effect of moisture content on conductivity were investigated in this work. The moisture content of samples was regulated by adding distilled water or by drying. Moisture content ω was determined according to the following relation:

$$\omega = \frac{m_1 - m_2}{m_1} 100\% \quad (9)$$

where:

- m_1 – weight of sample
- m_2 – weight of dry sample

All measurements were carried out under an air temperature of 20 °C and 60 % relative humidity. Bulk density was determined by the weight of constant sample volume.

Results and discussion

The values of conductivity σ , dielectric constant ϵ_r and loss tangent $\tan \delta$ measured at a variable frequency f of electric field for the samples of popcorn grains are presented in Tables 1 and 2. The samples have a different moisture content w and bulk density ρ . The effect of moisture content on conductivity, dielectric constant and loss factor are shown in Figure 1, 4 and 5, and dielectric constant and loss factor in the function of frequency are

Table 1 Values of conductivity σ , dielectric constant ϵ_r and loss tangent $\tan \delta$ for popcorn grains

	$w = 2.1\%$		$w = 3.7\%$	
	$\sigma = 7.41 \times 10^{-6} \text{ S.m}^{-1}$		$\sigma = 7.86 \times 10^{-6} \text{ S.m}^{-1}$	
	$\rho = 832 \text{ kg.m}^{-3}$		$\rho = 818 \text{ kg.m}^{-3}$	
$f, \text{ MHz}$	ϵ_r	$\tan \delta$	ϵ_r	$\tan \delta$
1	4.42	0.03	4.72	0.039
2	4.34	0.015	4.65	0.025
3	4.25	0.01	4.52	0.019
4	4.17	0.008	4.46	0.011
5	4.09	0.007	4.41	0.009
6	4.25	0.005	4.35	0.009
7	4.01	0.005	4.29	0.008
8	3.93	0.004	4.22	0.008
9	3.79	0.004	4.19	0.007
10	3.82	0.004	4.21	0.007
11	3.78	0.003	4.19	0.006
12	3.76	0.003	4.11	0.006
13	3.79	0.003	4.02	0.005
14	3.76	0.003	4.02	0.005
15	3.74	0.002	4.05	0.005
16	3.68	0.002	4.04	0.004

Table 2 Values of conductivity σ , dielectric constant ϵ_r and loss tangent $\tan \delta$ for popcorn grains

	$w = 9.9\%$		$w = 16.9\%$	
	$\sigma = 2.36 \times 10^{-5} \text{ S.m}^{-1}$		$\sigma = 4.11 \times 10^{-5} \text{ S.m}^{-1}$	
	$\rho = 777 \text{ kg.m}^{-3}$		$\rho = 716 \text{ kg.m}^{-3}$	
$f, \text{ MHz}$	ϵ_r	$\tan \delta$	ϵ_r	$\tan \delta$
1	5.94	0.058	7.63	0.094
2	5.69	0.039	7.25	0.051
3	5.45	0.028	6.73	0.037
4	5.36	0.022	6.65	0.028
5	5.28	0.018	6.56	0.023
6	5.21	0.017	6.48	0.019
7	5.16	0.013	5.99	0.018
8	5.11	0.012	6.07	0.015
9	5.03	0.01	6.07	0.014
10	4.89	0.009	5.91	0.013
11	4.92	0.008	5.67	0.012
12	4.9	0.007	5.66	0.011
13	4.92	0.007	5.64	0.01
14	4.83	0.007	5.61	0.009
15	4.92	0.006	5.63	0.009
16	4.83	0.006	5.62	0.008

Figure 1 Effect of moisture content on the conductivity of popcorn grains **Figure 2** Dielectric constant of popcorn grains in the function of frequency of electric field

shown in Figures 2 and 3. The factors having the highest effect on these effects are also specified. The measurements indicate that grains must be included in the most complex objects. They are organic heterogeneous multi-component dielectrics. It was determined that the dielectric constant of popcorn grains decreases when the frequency of electric field increases. A decreasing tendency is most sharp at lower frequencies. The minimal decrease is at higher frequencies. This relationship is caused by the dipole moment of water molecules and may be the orientation of charged groups of macromolecules. In this case, an orientation polarisation occurs in electric field. This type of polarisation is highly dependent on frequency. Dipole macromolecules are not able to follow changes in the polarity of electric field.

Values of dielectric constant increase when the moisture content of samples increases. This effect is the consequence of a very high magnitude of dielectric constant of water in comparison with other components of grains. The effect of the moisture content of samples on loss tangent in the function of frequency has a similar course as the effect of these parameters on dielectric constant. Conductivity values increase when the moisture content of samples increases. This effect is caused by improvement of conditions for an electrolytic transport of charges by dissociated ions in a damp medium. It is known that electric properties are also related with the bulk density of material. Therefore, to ensure the definiteness of results, also bulk density values of samples have been introduced.

Figure 3 Loss tangent of popcorn grains in the function of frequency of electric field

Figure 4 Effect of moisture content on the dielectric constant of popcorn grains

Figure 5 Effect of moisture content on the loss tangent of popcorn grains

Conclusion

It can be concluded that the conductivity, dielectric constant and loss tangent of popcorn grains increase when the moisture content of samples increases, and dielectric constant and loss tangent decrease as the frequency of electric field increases. Similar results for other biological materials were presented by other authors (Nelson et al., 2007; You and Nelson, 1988; Lawrence et al., 1990). The relationship of the dielectric constant of popcorn grain samples provides a basis for the design of many commercial moisture-testing instruments. In the future, more measurements on a wider frequency range would be desirable.

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