Equipment for the determination of dielectric properties of vegetable tissue during its mechanical loading

J. Sobotka, J. Krejčí, J. Blahovec

Faculty of Engineering, Czech University of Life Sciences in Prague, Prague, Czech Republic

Abstract: The internal structures of agricultural products change substantially in the course of the products deformation. One of the main changes in this process is the loss of the water content and water solutions generally due to the squeezing out of the cellular sap. The water content can be detected also by electric conductivity measured at different frequencies. The precise measurement of the electric conductivity during the deformation of soft agricultural products can be used as a simple indicative method for the study of the processes that control the squeezing out of the cellular sap including the filtration abilities of the cellular walls. In the paper, the experimental equipment is described that is able to detect the impedance of the vegetable tissue specimens during their compression between two plates. The equipment determines the sample impedance from a direct measurement of three voltages in the circuit that contains the tested specimen. The equipment is able to analyse the specimen properties at more than ten different frequencies up to 1 MHz. The formulas for the calculation of the real and the imaginary components of the relative permittivity are also given.

Keywords: soft plant tissue; conductivity; permittivity; frequency; deformation; reversibility

The internal structures of agricultural products change substantially during their deformation (Dejmek & Miywaki 2002). At the same time, one of the main changes in this process is the loss of the water content due to the squeezing out of the cellular sap. The water content can be detected also by means of electric conductivity measured at different frequencies (Nelson & Trabelsi 2005). In biological materials, the water content is usually responsible for the permittivity-frequency spectral character in these materials (Schwan 1957; Kaatze 2005; Pissis 2005). Electromagnetic waves are used frequently in many disciplines of food science and food technologies. At present, the most frequent is the use of the microwave heating for the cooking and baking of food products (Wilson *et al.* 2002; Vollmer 2004). The main advantage of the microwave cooking consists in the quickness of the whole operation because the cooking proceeds continuously in the whole volume of the approximately homogeneous cooked body. The alternate electric power can be understood as low-frequency electromagnetic waves penetrating the specimen tested.

The interaction of electromagnetic waves with bodies can be rationalised in terms of complex relative permittivity that contains information either on electrical conductivity of the body (by imaginary part of the complex relative permittivity) or on the real permittivity (by real part of the complex relative permittivity) (Pakula 2003; Nelson & Trabelsi 2005). For this reason, the relative permittivity in the complex form is studied so frequently (Venkatesch & Raghavan 2004) and many special instruments for dielectric measurements were developed (Venkatesch & Raghavan 2005).

The impedance measurements of the real capacitor are the basis for the determination of the material dielectric properties at low frequencies (e.g. Krejčí 2007). This paper contains the description of an equipment developed for the standard determination of the basic dielectric parameters (real and imaginary parts of the complex permittivity) during the compression of small specimens prepared from soft vegetable tissues by cutting.

METHOD OF TESTING

The method is based on the testing of specimens prepared from soft vegetable products like bulbs, roots, or tubers by cutting with sharp knives, razor

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blades and/or cork borer. We consider specimens of cylindrical shape (approximately 15 mm in diameter and 20 mm in height) tested in axial direction by compression with deformation rate less than 0.05 mm/s. The mechanical tests were performed in a testing machine Instron 4464. The compression metallic isolated plates served at the same time as electrodes for the continual two point impedance measurement of the specimen tested. The measurements are planned to be replicated on 15 specimens at least.

The scheme of the electric circuit used for the determination of the specimen dielectric properties is given in Figure 1 (e.g. Krejčí 2007). The source of the signal in the circuit was a generator (Agillent Generator 33220A) working with sinusoidal signal (10 V as amplitude). In the serial circuit, the three AC voltages were measured continuously by three 34401A digital multimeters as shown in Figure 1. The measured voltages corresponded: to the normal stable Ohmic resistor (220 Ω) – U_N, the tested specimen U_S and the total voltage on the serial connection of the normal resistor and the tested specimen U_T. The frequency of the generator could be changed to different values in some periodical sequence. In our current tests (Blahovec & Sobotka 2007), the following frequencies were used: 0.1, 0.5, 1, 5, 10, 50, 100, 500 kHz periodically and for each frequency the above mentioned voltage data were stored. The whole process was controlled by a computer using the Agillent software VEE, version 7.

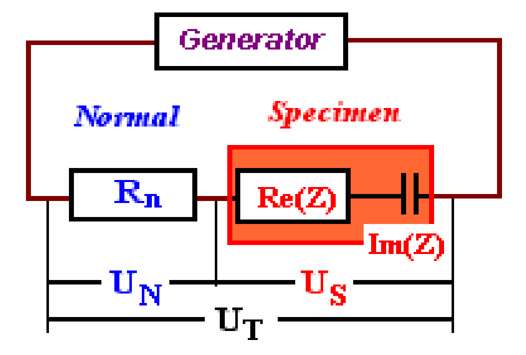

Figure 1. Scheme of the electric circuit for the determination of the specimen impedance; the circuit is formed by a voltage generator

The arrangement of the instruments linked to the testing machine is displayed in Figure 2. The data from the mechanical part of the test (time, displacement and force) were recorded every 0.1 s, the data in the electric part (time, frequency and the corresponding three voltages) were recorded every 1 s. The data were stored in two computers; the mechanical data and the electric ones separately had to be unified after the test on the base of the common time unit given by the computer controlling the testing machine by the standard Instron software.

The corresponding strain (ε_i) and stress (σ_i) values were the basic data in the mechanical tests and further calculations. The true (Hencky's) strain and stress were calculated as:

$$\varepsilon_t = -\ln(1 - \varepsilon_i) \quad (1a)$$

$$\sigma_t = \sigma_i(1 - \varepsilon_i) \quad (1b)$$

Figure 2. The electric equipment for the measurement of dielectric properties of the specimen during its mechanical testing; the testing machine Instron is in the left part of the photo with the tested specimen fixed below the loading cell in the Faraday cage; in the right upper part is the electric part of the equipment formed by normal resistor, signal generator, three multimeters and the data logger saving the common data scale between the testing machine and the electric part

Evaluation of the electric data

At first we suppose that the tested specimen is formed as a serial connection of the resistor and capacitor represented by the real and imaginary parts of the specimen complex impedance. The imaginary part of the impedance of the normal resistor can be omitted, so that for the impedance Z of the specimen (Figure 1) the following equation has to be fulfilled:

$$\frac{Z}{Z_N} = \frac{U_S}{U_N} \tag{2a}$$

where:

$Z_N = R_n$ – impedance of the normal resistor

U_S, U_N – voltages measured in the circuit (Figure 1).

The square power of the specimen impedance can be then expressed as:

$$|Z|^2 = \mathrm{Re}(Z)^2 + \mathrm{Im}(Z)^2 = \left(\frac{U_S}{U_N} R_n\right)^2 \tag{2b}$$

Similarly, we can obtain for the square power of the total impedance Z_T (impedance of the whole circuit, corresponding to voltage U_N in Figure 1.

$$|Z_T|^2 = \mathrm{Re}(Z)^2 + 2\mathrm{Re}(Z)R_n + R_n\,\mathrm{Im}(Z)^2 = \left(\frac{U_T}{U_N} R_n\right)^2 \tag{2c}$$

Combination of Eq. (2b) and (2c) gives then the final equations for the real and imaginary parts of the specimen impedance (Sobotka *et al.* 2006):

$$\mathrm{Re}(Z) = \frac{R_n}{2}\left[\left(\frac{U_T}{U_N}\right)^2 - \left(\frac{U_S}{U_N}\right)^2 - 1\right] = \frac{R_n}{2U_N^2}\left[U_T^2 - U_S^2 - U_N^2\right]$$

$$U_T^2 - U_S^2 - U_N^2 \geq 0 \tag{3a}$$

$$\mathrm{Im}(Z) = \frac{R_n}{2U_N^2}\sqrt{2(U_T^2U_S^2 + U_T^2U_N^2 + U_S^2U_N^2) - (U_S^4 + U_N^4 + U_T^4)} \tag{3b}$$

Analysing the tested specimen as a dielectric body, the model of the real capacitor is preferred (Krejčí 2007), so that the parallel resistor and capacity connection has to be accepted and reciprocal value of the complex specimen impedance has to be calculated, so that:

$$\mathrm{Re}\left(\frac{1}{Z}\right) = \frac{\mathrm{Re}(Z)}{\mathrm{Re}(Z)^2 + \mathrm{Im}(Z)^2} = 1/R \tag{4a}$$

$$\mathrm{Im}\left(\frac{1}{Z}\right) = \frac{\mathrm{Im}(Z)}{\mathrm{Re}(Z)^2 + \mathrm{Im}(Z)^2} = -\omega C \tag{4b}$$

where:

R – specimen resistance and $1/\omega C$ specimen capacitance.

In the real measurement, the capacitance of the specimen capacitance in Eq. (4b) contains also the capacity of connections and the jig that is used for the specimen fixation. The simplest way of correcting this influence is to presume some additional capacity parallel to the specimen capacity. This capacity can be detected by the measurement of impedance (Z_0) of the equipment without any specimen inside at some defined angular frequency ω_0, calculating the corresponding imaginary part of the impedance reciprocal value:

$$\mathrm{Im}\left(\frac{1}{Z_0}\right) = \frac{-\mathrm{Im}(Z_0)}{\mathrm{Re}(Z_0)^2 + \mathrm{Im}(Z_0)^2} = -\,\omega_0 C_0 \tag{5a}$$

The corrected value of Im(1/Z) is then obtained by subtraction of the value obtained:

$$\mathrm{Im}\left(\frac{1}{Z_0}\right)_{\mathrm{corr}} = \mathrm{Im}\left(\frac{1}{Z}\right) - \frac{\omega}{\omega_0}\mathrm{Im}\left(\frac{1}{Z_0}\right) \tag{5b}$$

where:

ω – actual angular frequency.

The measurements at higher frequencies are usually used as a basis for the corrections; in our experiments $\omega_0 = 2\times10^5\pi$ was used.

The corrected reciprocal values of the complex impedance Z of the specimen served as the basis for the calculation of the dielectric properties (Blahovec & Sobotka 2007). The relative permittivity εr of the potato tissue is then calculated as:

$$\varepsilon_r' = -\mathrm{Im}\left(\frac{1}{Z}\right)_{\mathrm{corr}} A \tag{6a}$$

$$\varepsilon_r'' = \mathrm{Re}\left(\frac{1}{Z}\right) A \tag{6b}$$

$$A = \frac{1}{2\pi f\varepsilon_0}\frac{l_0}{S_0}(1 - \varepsilon_i)^2 \tag{6c}$$

where:

ε_r' and ε_r'' – real and imaginary parts of the complex tissue relative permittivity,

$f = \omega/2\pi$ – signal frequency,

ε_0 – vacuum permittivity,

l_0 – initial specimen length,

S_0 – initial specimen cross section.

The term in brackets in Eq. (6c) represents the corrections of the changes of the dimensions of the deformed specimen, i.e. the change of its length and that of the cross section (see also Hencky's coordinates at Eq. (1a, b).

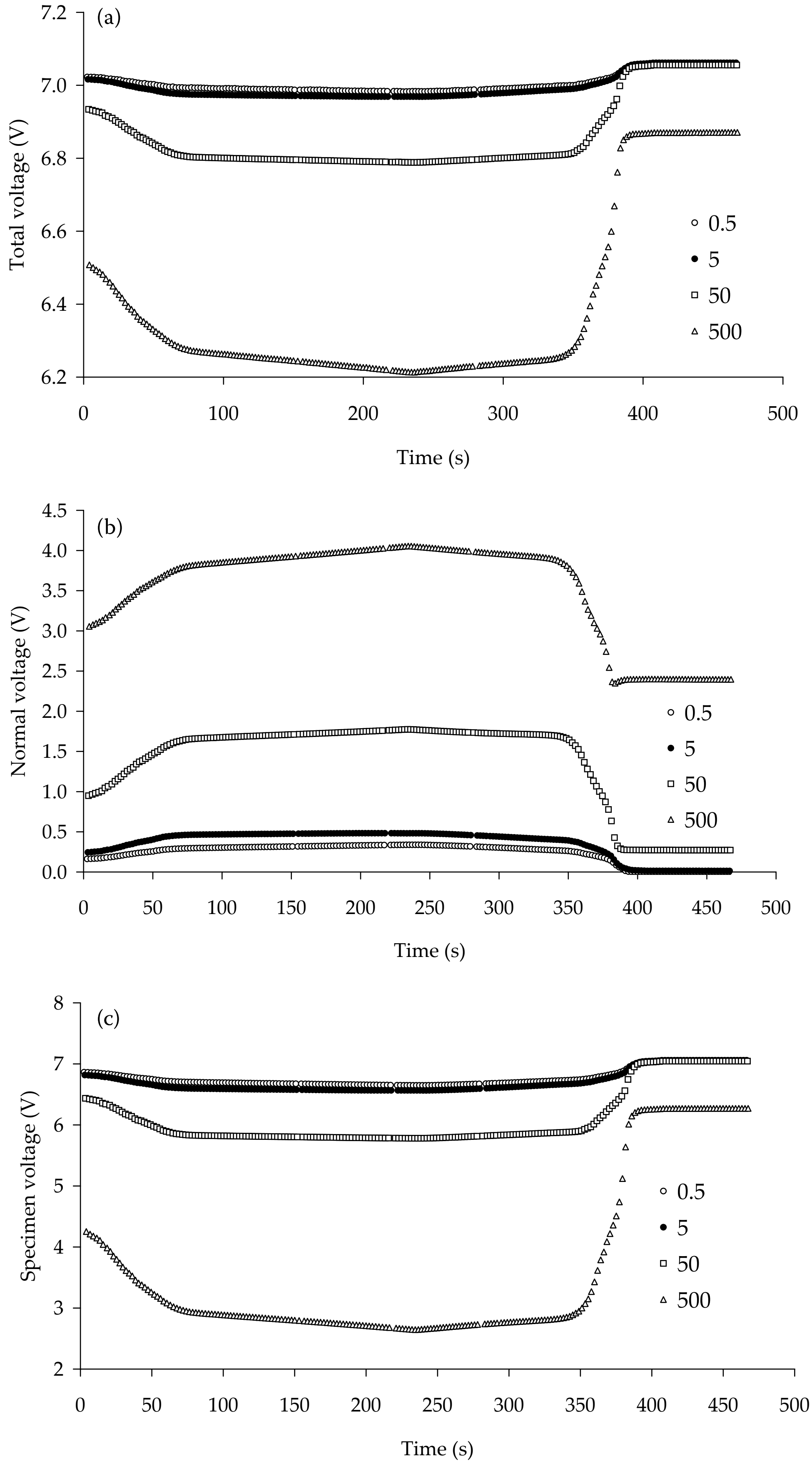

Figure 3. Typical voltage values measured on a potato specimen during the loading/unloading test (maximum compression strain 4%, corresponding time of the maximum loading: 239.3 s) versus time from the test start; numerical symbols in the figure determine the test frequency in kHz; (a) total voltage; (b) voltage on the normal resistor; (c) voltage on the specimen

Applications

We can demonstrate the proposed measurement on an example of one potato specimen tested in the loading/unloading test as described in Method. The maximum strain was about 4% that was reached at approximate time 239.3 s after the start of the test. The voltages measured in the test are given in Figure 3 for some selected frequencies. This figure shows that during the loading part of the test (i.e. at times lower then appr. 239.3 s), both the total and the specimen voltages decreased whereas at the same time the voltage on the normal resistor increased. During the unloading, the opposite trends were observed. The observed changes, even monotonic, differ in their progress; the sharper decrease of both the specimen and the total voltages in the first about 80 seconds of loading is changed to a slower decrease continuing up to the change of loading to unloading. A similar change of the voltage rate was observed in the unloading branch starting about 40 s before losing the contact between the electrode and the specimen. After losing the contact, the measured voltages were the same independently on time. At this stage of loading, the loading jig (Figure 2) operated as a capacitor.

The method of the impedance calculation – see Eq. (3a) and (3b) – is demonstrated in Figure 4. The data from Figure 3 were used for this demonstration. The calculated real and imaginary parts of the impedance behaved similarly as the specimen voltage. During the loading, the impedance parts decreased and similar steps in the loading were observed also in this case. The behaviour of impedance during the unloading part of the test was also similar to the behaviour of the specimen voltage. The application of the impedance to the calculation of the dielectric properties is presented elsewhere (Blahovec & Sobotka 2007).

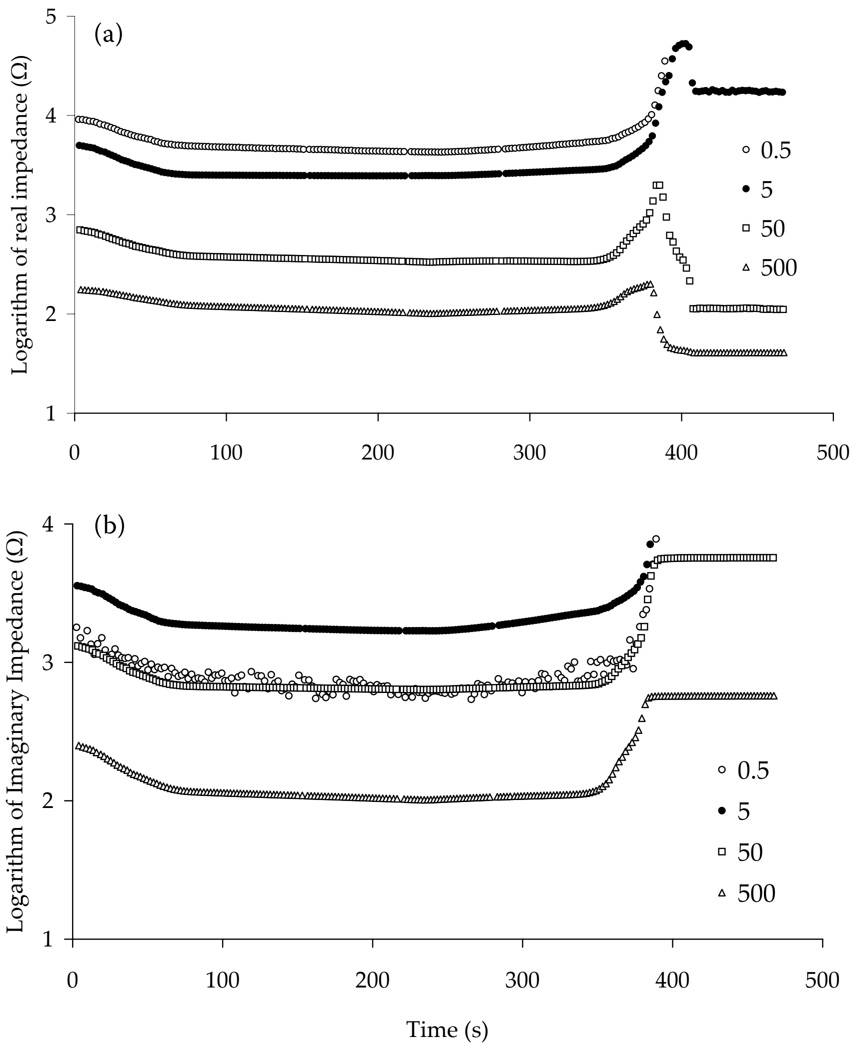

Figure 4. The impedance values calculated from the data in Figure 3 using Eq. (3a) and (3b); the logarithmic data are plotted versus time from the start test; numerical symbols are the same as in Figure 3; (a) real part of the impedance, (b) imaginary part of the impedance

CONCLUSIONS

The equipment built for the parallel impedance measurement during specimen loading was developed and demonstrated. The change of impedance during the test seems to be monotonic but with some separate characteristic parts of different rates. Some part of the impedance change is reversible.

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Abstrakt

Sobotka J., Krejčí J., Blahovec J. (2007): **Zařízení pro určování dielektrických vlastností zeleninového pletiva během jeho mechanického zatěžování.** Res. Agr. Eng., **53**: 143–148.

Vnitřní struktury zemědělských produktů se v průběhu deformace mění významným způsobem. Jedna z nejdůležitějších změn tohoto procesu je ztráta obsahu vody a vodních roztoků obecně v důsledku vytlačování buněčných šťáv. Vlhkost zemědělských produktů může být také určována prostřednictvím elektrické vodivosti měřené při různých frekvencích. Tak přesné měření elektrické vodivosti během deformace měkkých zemědělských produktů může být použito jako jednoduchá indikativní metoda pro studium procesů řídících vytlačování buněčných šťáv včetně filtračních schopností buněčných stěn. Práce obsahuje popis experimentálního zařízení, které je schopno registrovat impedanci vzorků z rostlinných pletiv během jejich stlačování mezi dvěma deskami. Zařízení zabezpečuje určení impedance vzorku měřením tří napětí v obvodu, jehož součástí je vzorek. Zařízení umožňuje analyzovat obvod při více než deseti frekvencích až do frekvence cca 1 MHz. Jsou odvozeny výrazy pro výpočet reálných a imaginárních složek relativní permitivity.

Klíčová slova: měkké rostlinné pletivo; vodivost; permitivita; frekvence; deformace; vratnost

Corresponding author:

Prof. RNDr. Ing. Jiří Blahovec, DrSc., Česká zemědělská univerzita v Praze, Technická fakulta, Kamýcká 129, 165 21 Praha 6-Suchdol, Česká republika
tel.: + 420 224 384 281, fax: + 420 234 381 828, e-mail: blahovec@tf.czu.cz