Potato tuber permittivity during deformation in compression

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Abstract: Potato tuber specimens of two varieties (Nicola and Saturna) were deformed in a compression loading/unloading test. The tuber complex permittivity spectrum at frequencies 0.1–500 kHz was measured repeatedly during the deformation. The results show that both parts of relative permittivity (real and imaginary) decrease with increasing deformation and vice versa. The same trend was observed at all studied frequencies even if it was not equally strong in all cases. The permittivity plots versus frequency were similar in both the tested varieties and in different stages of deformation. The influence of tuber deformation on the permittivity values as well as the reversibility of the permittivity changes during the deformation are changed substantially at strains about 20% in comparison to strains up to 10%. The obtained results support the hypothesis that permittivity measurements can serve as an alternative indication of the internal structural changes in potato tissue during its loading.

Keywords: potato; permittivity; frequency; deformation; strain; reversibility

The electromagnetic waves are used frequently in many disciplines of food science and food technologies. On the present, the most frequent is use of the microwave heating for cooking and baking of food products (Vollmer 2004; Wilson *et al.* 2002). The main advantage of the microwave cooking consists in quickness of the whole operation because the cooking proceeds continuously in the whole volume of the approximately homogeneous cooked body. The sources of the inhomogeneous heating consist mainly in inhomogeneous structure of the heated product. The microwave heating is well defined physically (Vollmer 2004) and depends on the proper dielectric properties of the heated body and on the character of the microwave used (Wilson *et al.* 2002).

The spreading of electromagnetic waves in agricultural products and/or foods is not limited to their heating only. 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) (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). In biological materials the most important role in forming their permittivity is played by the water content, which is usually responsible for the permittivity-frequency spectral character in these materials (Kaatze 2005; Pissis 2005).

The traditional knowledge of potato tubers is based on composition, structure and mechanical properties (Burton 1966; Mohsenin 1970). The dielectric properties of potato tubers were also studied starting from 1960s (lot of data was presented by Nelson, e.g. Nelson & Trabelsi 2005). It is believed that there exists some correlation between dielectric and mechanical properties (Dejmek & Miyawaki 2002; Pakula 2003) and that the detailed knowledge of dielectric properties can substitute some missing mechanical data for their practical use.

The dielectric measurements of potato specimens in this paper were performed directly during mechanical testing with the aim to determine relation between the dielectric and mechanical data in different stages of the tissue deformation.

MATERIALS AND METHODS

The varieties Nicola and Saturna cultivated in the same standard conditions (experimental sta-

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tion Valečov of Research Potato Institute close to Havlíčkův Brod) were tested in February 2006. The harvested tubers were cold stored in an air ventilated room at the temperature 6–10°C. After transport to laboratory the tubers were stored in a refrigerator for a few days at 7 ± 1°C. The day prior test the tubers were washed in cold water and then 20 defect-free tubers of mediate size (5 to 8 cm in diameter) were selected for one day testing. The testing of 60 tubers in every variety was divided into three days.

One specimen of cylindrical shape (approximately 15 mm in diameter and 20 mm in height) was cut from the central part of each tuber so that its axis was parallel to the stem-bud axis and the pith of the tuber was excluded preferably. A cork borer and special double knives were used for this purpose. After a more precise determination of the specimen's size, the specimen was deformed axially in compression in the loading/unloading test with the deformation rate 0.0167 mm/s. Three different levels of loading were used (maximum strains are in brackets): 1 mm (5%), 2 mm (10%), 4 mm (20%). The test with the given level was applied on 20 specimens tested within a day. The mechanical tests were performed in a testing machine Instron® 4464. The compression metallic isolated plates served at the same time as electrodes for a continual two point impedance measurement of the tested specimen. The measurement was based on three AC voltages determined by three 34401A digital multimeters in the net with serial connection of the Agilent Generator 33220A with signal 10 V, stable Ohmic resistor (220 Ω) and the tested sample. A generator frequency sequence 0.1, 0.5, 1, 5, 10, 50, 100, 500 kHz was used periodically and for each frequency the above mentioned voltage data were stored. The whole process was controlled by a computer using the Agilent software VEE, version 7. The method of measurement and calculation of the specimen impedance is more precisely described in a special paper (Sobotka *et al.* 2006, 2007).

The data from mechanical part of the test (time, displacement and force) were recorded every 0.1 s, the data in electrical part (time, frequency and the corresponding three voltages) were recorded every 1 s. The collected data were recalculated by a special Fortran programme. The data were based on the direct electrical measurements; the corresponding mechanical values were interpolated from rich data samplings available.

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

$$\varepsilon_i = -ln(1 - \varepsilon_i) \tag{1a}$$

$$\sigma_t = \sigma_i\,(1 - \varepsilon_i) \tag{1b}$$

For every test the hysteresis losses (*HL*) and degree of elasticity (*DE*) were also calculated using the following formulas:

$$HL = \frac{W_L - W_U}{W_L} \tag{2a}$$

$$DE = 1 - \frac{d_r}{d_m} \tag{2b}$$

where:

W_L, W_U – loading and unloading deformation works,

d_m, d_r – maximum and residual deformations.

The complex impedance Z of the specimen served as a basis for calculation of the dielectric properties. The relative permittivity ε_r of the potato tissue is then calculated as:

$$\varepsilon_r' = \mathrm{Im}\frac{1}{Z}\,A \tag{3a}$$

$$\varepsilon_r'' = \mathrm{Re}\frac{1}{Z}\,A \tag{3b}$$

$$A = \frac{1}{2\pi f \varepsilon_0}\,\frac{l_0}{S_0}\,(1 - \varepsilon_i)^2 \tag{3c}$$

where:

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

f – signal frequency,

ε_0 – vacuum permittivity,

l_0 – initial specimen length,

S_0 – initial specimen cross section.

The term in brackets in Eq. (3c) represents corrections to changes of dimensions of the deformed specimen, i.e. change of its length and cross section.

RESULTS AND DISCUSSION

Mechanical test

Figure 1 contains an example of forces measured in a typical loading/unloading test. The parameters given by Eq. (1a, b), i.e. hysteresis losses and degree of elasticity, were calculated for every test and the resulting mean values are plotted in Figure 2a, b. This figure shows that the hysteresis losses increase with the increasing loading level whereas the degree of elasticity decreases in the same case. It seems that

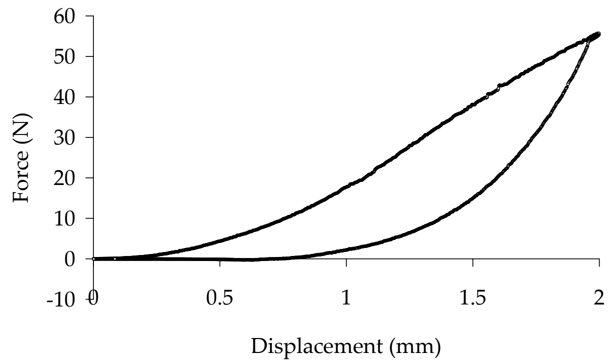


Figure 1. Typical course of a loading/unloading test (Nicola, loading up to strain 10%); the upper curve belongs to the loading branch and the lower curve to the unloading branch

both the quantities are highly correlated for both the tested varieties under the test conditions.

Electrical data

The hysteresis observed for the electrical data had rather different character than the hysteresis observed at mechanical data. Whereas the mechanical stress increased with increasing strain, the electrical parameters decreased with increasing strain. During unloading, the stress decreased to zero at nonzero strain, but our electrical quantities (i.e. parts of complex permittivity) at the same conditions stopped their increasing prior to reaching the zero strain at the same conditions. The typical development of the basic electrical quantities in Nicola tissue in an experiment with the maximal strain (20%) is given in Figure 3. In case of loss tangent no return was observed during unloading, the loss tangent continued in depression during the unloading stage of the specimen test. But not the same development of the electrical quantities was observed in all the studied cases with different frequencies as well as different levels of loading.

Spectral dependence of the initial electrical data. At low levels of loading, both parts of the relative permittivity rather increased with increasing loading. It can be detected on the initial parts of the plots in Figure 3a, b. This behaviour and formation of the permittivity maxima in the initial parts of these plots seem to be connected with some improving of the contact between the both electrodes with deformed specimen by increasing contact pressure. For this reason the values at the local maxima are interpreted as the initial permittivity values. The initial permittivity values are illustrated in Figure 4; the Figure is based on the data obtained in test with the highest level of loading (strain 20%). The figure shows a small but systematic difference between both varieties. The results are comparable to previous measurements on the variety Radka (Blahovec & Million 1985); greater deviations were detected only for the imaginary part of permittivity.

Something like "a plateau" observed for ε' part at log(*f*) = 3–5 indicates participation of the dispersion processes that is usually denoted as β (Schwan 1957), indicating the basic properties of cellular structure including of cell wall properties (see also electrical modelling of the cellular structure by Blahovec & Million 1985).

Change of permittivity due to deformation. Both the parts of the relative permittivity decreased with increasing loading and at least partly these decreases were reversible during unloading parts of tests (Figure 3a, b). The information about relative decrease of permittivity during the loading period is given in Figure 5a, c. This Figure shows that differences between both the tested varieties were not too high even the variety Nicola seems to be more sensitive to loading in most cases. The effect is stronger at the real part of the permittivity in comparison with the imaginary one. The sensitivity to loading also depended on current frequency but in different manner for the real and the imaginary parts: the relative decrease of real part of permittivity decreased with increasing frequency, whereas the opposite trend was observed at imaginary part.

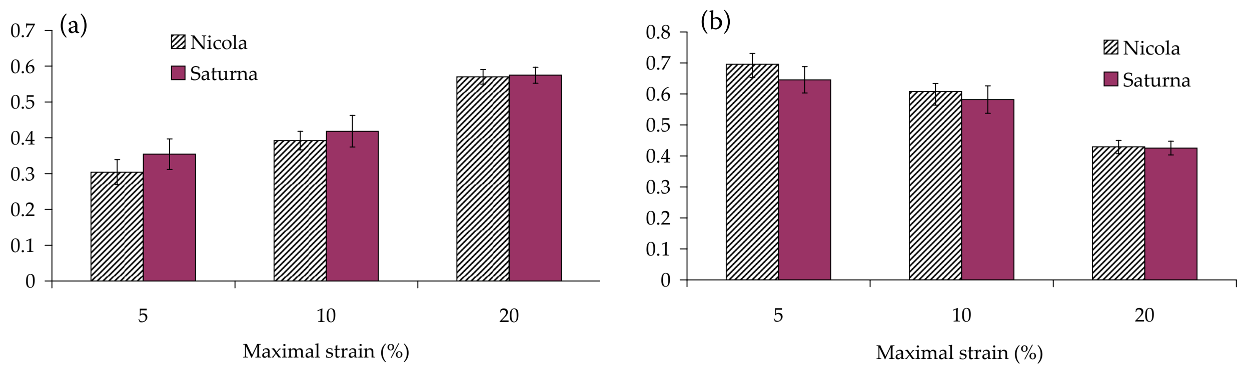
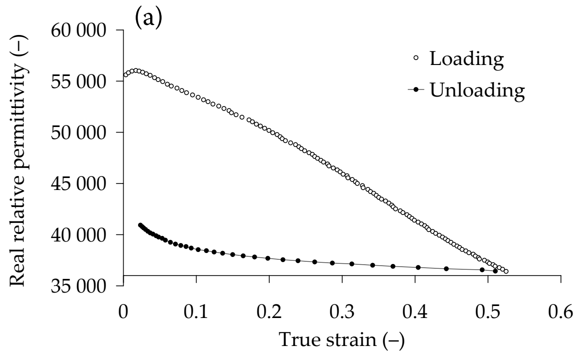
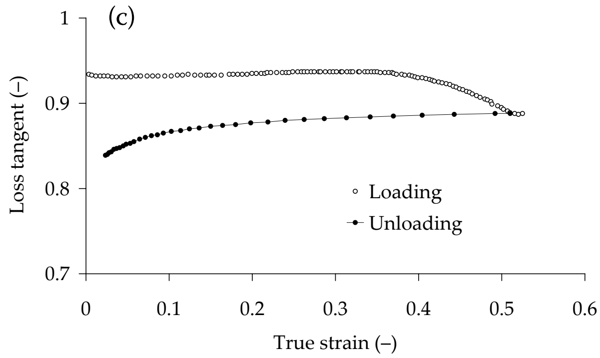


Figure 2. The main mechanical parameters in a loading/unloading test: (a) hysteresis losses; (b) degree of elasticity





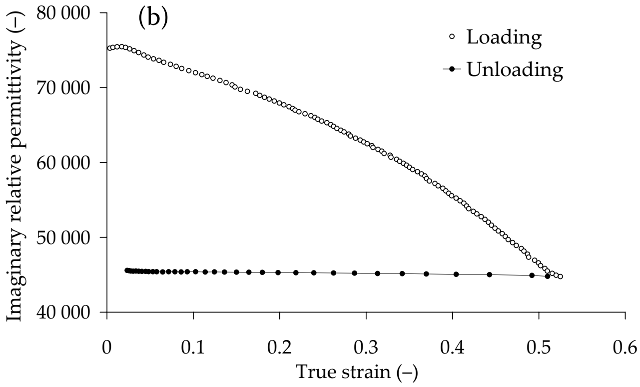


Figure 3. Typical course of dielectric properties at 5 kHz frequency during the loading/unloading test (Nicola, loading up to 20% strain) – plotted versus true strain; the upper curve belongs to the loading branch and the lower curve (in colour) to the unloading branch: (a) the real part of permittivity; (b) the imaginary part of permittivity; (c) loss tangent, i.e. atan(IPP/RPP), where IPP and RPP are the imaginary part of permittivity and the real part of permittivity, respectively

An important property of the permittivity changes is the partial reversibility of the changes (Figure 3a, b). Figure 5b, d shows that at low deformations (5%) the permittivity of a specimen after loading and unloading was higher than before the test, i.e. plotted ratios in Figure 5 b, d are higher than 1. This effect can be caused at least partly by stress formation of the more rectangular specimen that has a better contact with electrodes at the end of the test. The observed effect decreased with increasing loading. Moreover, the effect is a function of the current frequency; the real part of permittivity increased after unloading more at higher than at lower frequencies (Figure 5b). The opposite effect was observed at imaginary part of permittivity where at lower loading levels the permittivity increase after unloading decreased with increasing frequency (Figure 5d).

The permittivity reversibility depended also on the level of loading; with increasing level of loading the reversibility of permittivity fell down and also dependences of permittivity on frequency were changed (Figure 5b, d). At strains 10% the unloading was observed as nearly reversible process with nearly the same permittivity values before and after loading. Further increase of level of loading to strains 20% was followed by an important loss of reversibil-

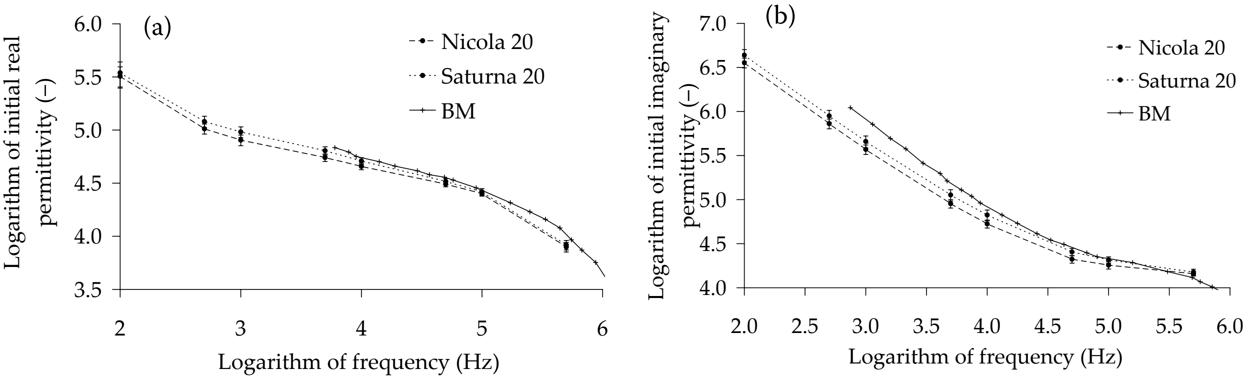


Figure 4. The initial tissue permittivity plotted against frequency for varieties Nicola and Saturna loaded prior unloading up to 20% strain; BP means results of measurements obtained previously (Blahovec & Million 1985) in another experimental arrangement at the variety Radka; the bars denote standard deviation for 20 tested specimens: (a) real part of permittivity; (b) imaginary part of permittivity

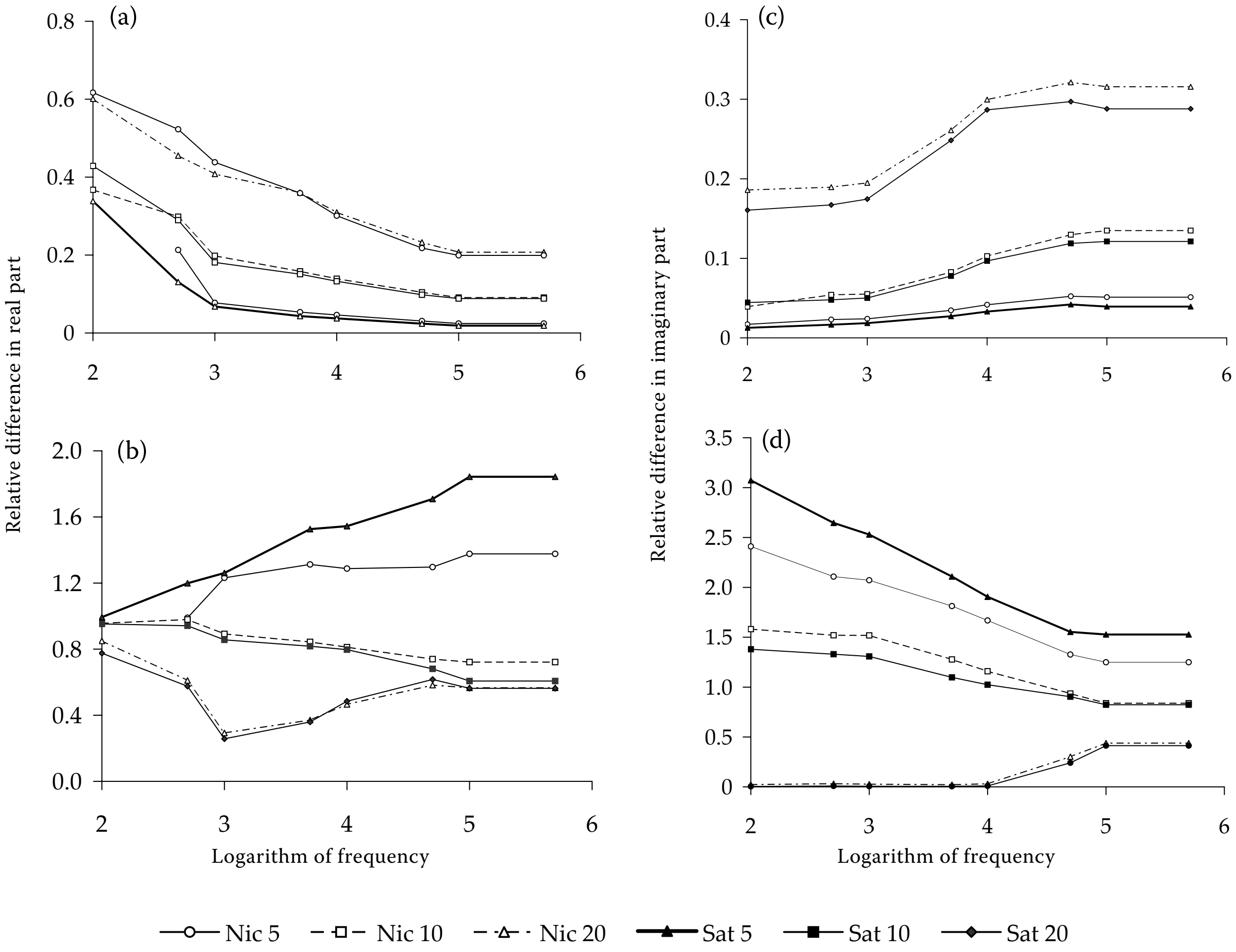


Figure 5. Mean values of parameters describing changes of the relative permittivity components during compression of potato tissue: (a) relative change of real permittivity during loading (i.e. maximal real permittivity at the beginning of loading minus real permittivity at maximum loading divided by maximal real permittivity at the beginning of loading) plotted against logarithm of frequency; (b) ratio of real permittivity decrease during loading and real permittivity increase during unloading; (c) relative change of imaginary permittivity during loading, similarly as it was defined for the real part at (a); (d) ratio of imaginary permittivity decrease during loading and imaginary permittivity increase during unloading, see (b); Nic and Sat denote varieties Nicola and Saturna, respectively; numbers at the variety abbreviations denote the strain level in per cents

ity in permittivity. This behaviour of permittivity in relation to loading forms the main difference to the stress characteristics: hysteresis losses and degree of elasticity. Both stress characteristics were changed with increasing loading monotonically and nearly proportionally to the level of loading. The indicators of the permittivity reversibility do not give such a simple relationship (Figure 5b, d).

CONCLUSIONS

The potato tissue permittivity decreases with increasing level of loading; the decrease of the permittivity real part is reduced with increasing frequency of the current, whereas the decrease of the permittivity imaginary part is enlarged with increasing current frequency. The tissue permittivity at low level loading (up to strain 5%) is a reversible quantity. Moreover, the values after loading are higher than before loading and this effect is stronger at higher frequencies for the real part of permittivity and at lower frequencies for the imaginary part of permittivity. The role of loading as a factor influencing the permittivity values is more pronounced at strain 20% in comparison to 10% strain.

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Abstrakt

Blahovec J., Sobotka J. (2007): **Permitivita hlíz brambor během deformace tlakem**. Res. Agr. Eng., **53**: 79–84.

Vzorky z hlíz dvou odrůd (Nicola a Saturna) byly deformovány v tlakovém zatěžovacím a odtěžovacím testu a během tohoto procesu byla opakovaně měřena spektra komplexní permitivity při frekvencích z intervalu 0,1–500 kHz. Výsledky ukazují, že obě části relativní permitivity (reálná a imaginární) klesají s rostoucí deformací a naopak. Stejný trend byl pozorován při všech studovaných frekvencích i když nebyl stejně silný ve všech případech. Závislosti permitivity na frekvenci byly podobné pro obě studované odrůdy a různá stadia užité deformace. Vliv deformace na hodnoty permitivity a reversibilita změn permitivity v důsledku deformace se výrazně lišila při relativních deformacích 20 % ve srovnání s relativními deformacemi 10 % a nižšími. Získané výsledky podporují hypotézu, že permitivita může sloužit jako alternativní indikátor změn vnitřní struktury dužniny brambor při jejím mechanickém zatěžování.

Klíčová slova: brambory; permitivita; frekvence; deformace; relativní deformace; vratnost

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