THERMAL ANALYSIS OF POTATO AND CARROT TISSUES AFTER PROCESSING BY PULSED ELECTRIC FIELD

Jiří BLAHOVEC[1], Pavel KOUŘÍM[1]

[1]*Department of Physics, Czech University of Life Sciences in Prague, Czech Republic*

Abstract
The article is focused on DiElectric thermal analysis of potato and carrot tissues during heating from 30 to 90 °C with possible application of pulsed electric field. Our results show that the temperature scale can be divided into subcritical, critical (70-80 °C) and supercritical parts. Big changes are detected in the critical stage and there are combined with destruction role of the electric field. Destruction role of high temperature and electric field is resulted by the capacity changes in the supercritical change. The observed destruction is higher in potato. This difference can be caused by a destruction role of swelling potato starch.

Key words: *dielectric; thermal analysis; model; resistance; capacitance.*

INTRODUCTION
The main part of a cooking process used to bring the product texture to such a state that is savoury to a consumer. Recently, the combination of the thermal processing with the application of electric pulses (PEF – pulse electric field: application of short electric pulses of high potential) has been proposed for this purpose (*Blahovec, Lebovka, & Vorobiev 2017*). Previously, it was known that the application of an external pulsing electric field (*Tsong & Su, 1999; De Vito et al., 2008; Vorobiev & Lebovka, 2010*) can damage the integrity of cellular membranes. The disintegration effect of the PEF application to a cellular product is determined by parameters of the pulse procedure, by temperature of the thermal processing and also by the time schedule (*Asavasanti, Stroeve, Barrett, Jernstedt, & Ristenpart, 2012*) of the whole process that is termed pulse protocol.
The important role of temperature as an external parameter for living matter is generally known and there is used as a fundamental technological parameter in cooking of most biological products. There is still lack of information about details of the parallel processes taking place in living cells and tissues during heating (*Vilgis, 2015*). The indirect methods has to be used in this cases, in which only some characteristic states are indicated. For such purposes the methods of thermal analysis (*Haines, 2002*) were developed, provided that specimens' drying due to increasing temperature is prevented (*Blahovec, Lahodová, & Zámečník, 2012; Xu, & Li, 2014*). The combination of electric pulses and simple heating procedures could form a new way of processing in the culinary area and cooking technology. Any reduction of heating in food processing is a source of energy conservation and reduction of food components losses. This is important mainly in fruits and vegetables where heating is followed by losses of vitamins and other unstable important nutrients. Combination of two experimental technics: DMA – Dynamic Mechanical Analysis and DETA – DiElectric Thermal Analysis, see *Haines, 2002*) was used in our previous papers (*Blahovec & Kouřím, 2019a,b*) for studying the changes caused by electric pulses in potato and carrot. It was found that application of PEF causes nontrivial changes of the tested specimens at temperatures 30-90 °C. Even if some changes can be classified as "additive" to the changes caused by temperature, the development some of them can be classified as rather strange (see also *Imaizumi, Tanaka, Hamanaka, Sato & Uchino, 2015; Vorobiev & Lebovka, 2010).*
The aim of this paper is to include some knowledge into differences in behaviour of potato and carrot during their heating in DMA and DETA tests (at temperatures 30-100 °C). For this purpose, the data that were obtained for potato and carrot in two separated research projects in last two years (*Blahovec and Kouřím, 2019a,b*) were used. In these projects, the same PEF protocols were applied to the specimens of the same dimensions so that the obtained electrical parameters can be compared directly.

MATERIALS AND METHODS

The carrots used (variety Jereda) were cultivated in the university garden (for details see *Blahovec & Kouřím, 2019b*) and potatoes were produced by Potato Research Institute in Havlíčkův Brod (Czech Republic) – see *Blahovec & Kouřím, 2019a.*

Rectangular specimens (5.1 - width × 3.8 - thickness × 35 - length) mm with their long axis parallel to the root grow direction were cut from the external part of a root (carrot) or the internal parenchyma (potato) by a knife using special cutting jigs keeping constant the dimensions and the rectangular shape of the specimens. The following procedures were performed with every specimen: measurement of its impedance after its fixation to the DMA tester (see further) at temperature 20 °C (the initial specimen impedance).This measurement gave the initial values of the specimen impedance: real component R_0 and imaginary component X_0. The DMA instrument was arranged so that the electric properties of the tested specimen could be continuously measured as a real conductor described by the complex impedance: an RLC meter (Hameg 8118 with voltage 1 V eff, frequency 20 kHz and 3 sampling per minute) was used for this purpose. The specimen was carefully mechanically fixed in two points so that the longitudinal axis was perpendicular to the fixing jaws. The free length of the specimen between the jaws was 10.8 mm. The height of the fixed specimen was appr. 3.8 mm.

One set of the specimens (5 repetitions) was used for a standard DMA/DETA test (*Blahovec & Kouřím, 2019a*); this set was denoted as the basic, shortly b. One of the jaws was fixed and the other was moving up and down with constant amplitude of 0.5 mm and a frequency of 0.2 Hz in the dynamic cantilever test. The force necessary for the oscillation was recorded, being the basis for the complex modulus determination. Every experiment started at 30 °C. The air humidity in the test chamber (90 %,) was kept constant during the whole experiment. The control of the air humidity in the test chamber was based on direct humidity measurement by a special hygrometer and water vapour ejection into the chamber. The temperature scan proceeded up to 90 °C with a rate of 1 K/min.

The results of the DETA test were analysed on temperature plots of the impedance components: real R_r and imaginary X_r. Also, in this case, we preferred to present the results of our experiments as relative results: $R = R_r/R_0$, and $X = X_r/R_0$, where R_0 is the initial value of the real component of the specimen at 20 °C. This recalculation helps to reduce potential dimensional and surface variations in the prepared specimens. We used simple electrical model of the tested tissues as a parallel connection of a resistor R_e and a capacitor C giving by the following formulas:

$$R_e = \frac{R^2+X^2}{R}; \qquad \omega C = \frac{-X}{R^2+X^2} \tag{1}$$

where ω is the circular frequency of the electric current.

The specimens included in the sets for further testing (5 repetitions in every case) were removed from the DMA instrument after measurement of the initial impedance (see above) and prepared for PEF loading. It was done in a special equipment between two steel electrodes 2 cm in diameter that were placed in the central parts of the specimen perpendicularly to their 5.1 x 35 mm^2 sides. Pulse loadings were performed using a special equipment: the basic AC sinusoidal signal with a frequency of 20 kHz was modulated into a nearly rectangular form of 10 ms length and height corresponding to the field intensity of 500 V/cm into the tested specimen. In this paper we will limit to the case that was denoted in previous papers (*Blahovec and Kouřím, 2019a,b*) as e: the set of specimens loaded by two pulses with interval 1 s. Using this information, we determined for every specimen its initial parameter R_0 that plays key role of the norm for calculation of R and X after pulsing. Specimens included into set e were tested just after pulsing in the same DMA/DETA combined test as the specimens of the basic test (b).

The results obtained in at least five replications were analysed using the standard laboratory software Origin®, OriginPro Ver. 7 (*OriginLab, Northampton, MA, USA*). The data obtained for a specimen set were unified into a group of data. This group of data was classified according to temperature and analysed sequentially so that the results of all measurements falling into interval of one centigrade increase were evaluated statistically and the corresponding mean values and standard deviations were calculated by a special FORTRAN programme. The applied sampling of data (3 per minute), the rate of heating

(1K/minute) and 5 repetitions of the measurement led to the final statistics of at least 15 measurement for one point/K in the analysed temperature scale. For proving statistical hypotheses 95 % level is used.

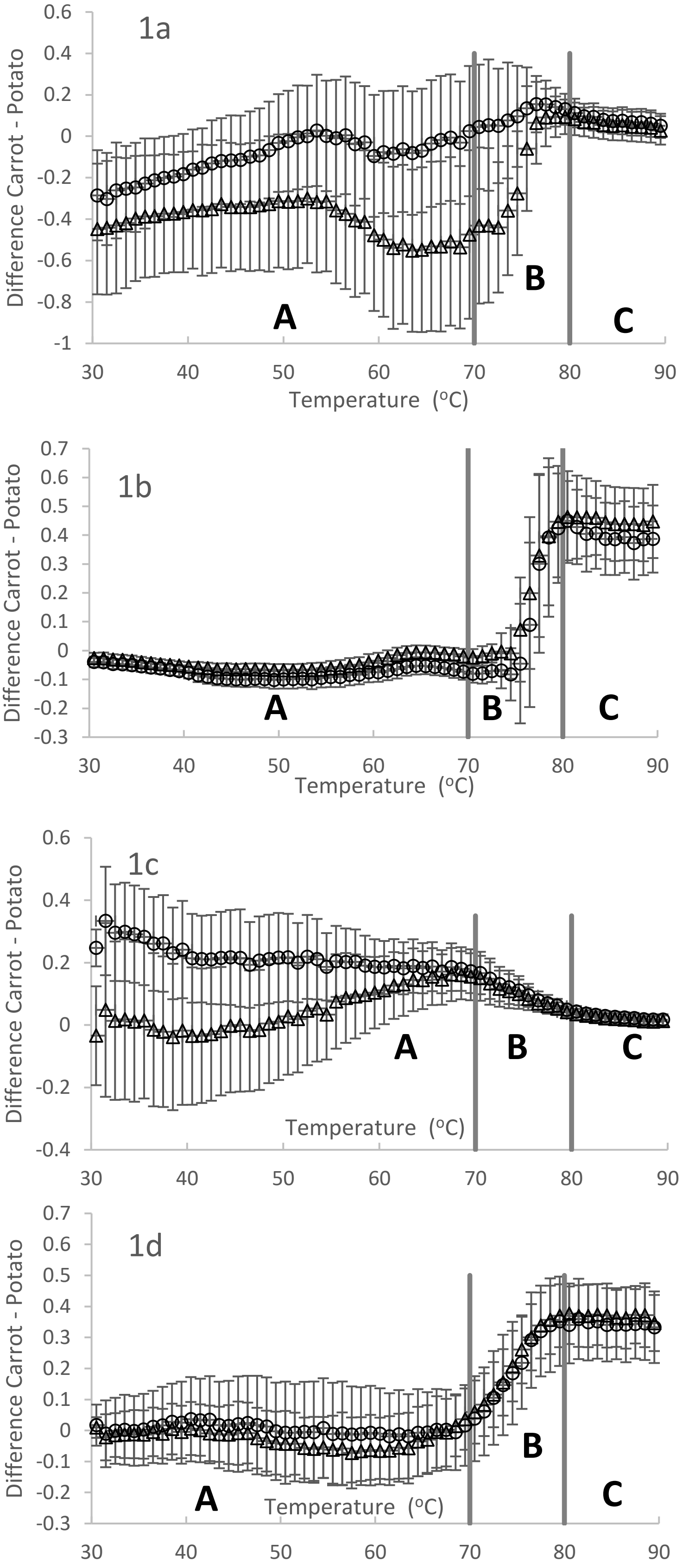

Fig. 1 Difference between values obtained for carrot and the corresponding values for potatoes (triangles mark data for Dali and rings mark data for Agria). The bars represent estimation of standard errors. 1a and 1b: specimens without PEF application, 1c and 1d: specimens after PEF application. 1a and 1c denote R_e ; 1b and 1d denote data for capacitance. The marks A, B, and C denote respectively subcritical, critical and supercritical stages in tissue cell wall transformations *(Blahovec & Kouřím, 2019a,b)*.

RESULTS AND DISCUSSION

We will concentrate to differences that we obtained between the values given by Eq. (1) for carrot and potatoes. The resulting data are given in Fig. 1. This figure illustrates either different role of PEF or the potato variety in the DETA plots. Figure 1 shows that the obtained differences in the basic states (without PEF application) are accompanied by a higher level of statistical error at the resistivity of tissue (Fig. 1a) than at its capacitance (Fig. 1b). In stage A and at the lower temperatures in stage B the dispersion of the capacitance data for products without application of PEF is so low that we are able to detect differences in capacitance between different potato varieties: the capacitance of Dali is lower than the capacitance of Agria. The increasing level of statistical dispersion in stage B causes loss of possibility to detect any differences between varieties at higher temperatures. Application of PEF to the tested tissues leads to higher statistical dispersions in the capacitance differences even in the subcritical stage (Fig. 1d) and it also leads to lack of capacitance differences between different potato varieties. At the stage B, there is observed a big change of all differences presented in Fig. 1. Whereas in case of resistance these changes lead to reduction of the differences in the absolute values, in case of capacitance the changes lead to increases of the differences in the positive values. This trend means that in the stage B the differences between carrot and potato in resistance decrease and the opposite change was observed for capacitance differences. Both quantities: the resistance and the capacitance in stage C are approximately constant and of the same value for both potato varieties (see Table 1). But whereas the resistances of all the tested tissues (carrot and two varieties of potato) are approximately the same in stage C (the difference in Table 1 is close to zero in all cases), the capacitance of carrot is much higher than capacitance of potato (Table 1 and Fig. 1b,d). The obtained differences in the capacity of carrot comparing to the potato in stage C indicate that in stage C there still exists some important structural difference between the potato and carrot structures. This difference cannot have important influence on the tissue conductivity whereas it should play the important role in the tissue capacity. Under our opinion, the high difference in capacitance could be caused by the primary cell walls that are destroyed in potatoes in stage B by the swelling starch, but they still exist in carrot. The primary cell walls in carrot can form some structure that is responsible for the observed capacitance differences between potato and carrot (Fig. 1b,c).

The critical stage (B) is typical by destruction of cellular structure, for potato *see Imaizumi et al. (2015).* Our previous results on potato and carrot (*Blahovec & Kouřím, 2019a,b*) showed that the model capacitance responds in this stage a typical peak that could be reduced by the PEF treatment. The capacitance differences in Figs. 1b, 1c are without any peak, it means that the peak has the same shape either for carrot or potatoes, so that the peaks are cancelled by the applied difference operation.

Tab. 1 Mean carrot-potato differences of model parameters in stage C

Product and parameter	b Without PEF	e With PEF
Dali - R_e	0.054	0.020
Agria - R_e	0.078	0.026
Dali - Capacitance	0.449	0.368
Agria - Capacitance	0.400	0.345

Figure 1 shows that the difference operation gives for R_e variable results that limit our ability to distinguish the variety differences for potatoes. In the basic state (Fig. 1a) and at the initial temperature the plotted difference is less than zero for both potato variety, so that the relative resistance of potato is higher than the relative resistance of carrot. With increasing temperature the plotted difference increases for both potato varieties. In case of Agria we are not able to prove difference in R_e between carrot and potato at temperatures above cca 40 °C. In case of Dali we obtained different results. The difference in R_e between carrot and potato of this variety can be proved at temperatures lower than 75 °C: in this temperature range there is relative resistance of potato variety Dali higher than the relative resistance of carrot. The highest difference in R_e between carrot and potato variety Dali was observed at temperature about 65 °C and in temperature range 50-75 °C it can be proved that R_e in var. Dali is higher than in Agria.

After application PEF the results are little different, because the relative resistance is changed not only in potatoes but also in carrot. At the lowest temperatures, up to about 55 °C the relative resistance of Dali behaves similarly as in carrot; after small decrease at higher temperatures (55-80 °C) it moves to the carrot values in the range C (the resistance difference moves to zero – Fig. 1c, see also Table 1). In case of Agria we observed at low temperatures values of R_e lower than the corresponding values for carrot. The different behavior of Agria and Dali can be proved up to temperature about 55 °C. After reaching this temperature the relative resistance of Agria behaves similarly as in Dali. It could be concluded that the PEF application leads to reductions of differences between potatoes of different varieties.

CONCLUSIONS

The electric behavior of carrot and potato during its heating up to 90 °C can be classified into three stages: subcritical (up to about 70 °C), critical, and supercritical (above about 80 °C). The electric properties of the tested products were described by a simple model with parallel connected resistor R_e and capacitor with capacitance ωC. In supercritical stage all parameters are relatively stable, and R_e is approximately the same for all the tested products. This is not true for capacitance: its value for carrot is much higher than for potato (variety difference was not proved). In subcritical stage of the tissues in the basic state, the capacitance is highly stable so that the variety differences can be detected. PEF application leads to the increasing level of statistical dispersion so that no variety differences in the capacitance can be observed. The relative resistance in the subcritical stage is accompanied by a higher level of statistical dispersion even in the basic state. Differences between different varieties can be proved also in the subcritical stage, but only in some special cases.

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REFERENCES

1. Asavasanti, S., Stroeve, P., Barrett, D.M., Jernstedt, J.A., & Ristenpart, W., (2012). Enhanced electroporation in plant tissues via low frequency pulsed electric fields: Influence of cytoplasmic streaming. *Biotechnological Progress 28*, 445-453.
2. Blahovec, J. & Kouřím, P. (2019a). Pulsed electric stimulated changes in potatoes during their cooking: DMA and DETA analysis. *Journal of Food Engineering 240*, 183-190.
3. Blahovec, J. & Kouřím, P. (2019b). Cooking of carrot previously processed by PEF: DMA and DETA analysis and comparing with Potato. *Innovative Food Science and Emerging Technologies,* in submission.
4. Blahovec, J., Lahodová, M. ,& Zámečník, J., (2012). Potato DMA analysis in area of starch gelatinization. *Food and Bioprocess Technology, 5*, 929–938.
5. Blahovec, J., Lebovka, N. & Vorobiev, E. (2017). Pulsed Electric Fields Pretreatments for the Cooking of Foods. *Food Engineering Reviews 9*, 226-236.
6. De Vito,F.,Ferrari, G., Lebovka, N.I.,Shynkaryk, N.V., & Vorobiev,E., (2008). Pulse duration and efficiency of soft cellular tissue disintegration by pulsed electric fields. *Food Bioprocess Technology 1*, 307-313.
7. Imaizumi, T., Tanaka, F., Hamanaka, D., Sato, Y., & Uchino, T., (2015). Effects of hot water treatment on electrical properties, cell membrane structure and texture of potato tubers. *Journal of Food Engineering 162*, 56-62.
8. Haines, P.J. (2002). *Principles of thermal analysis and calorimetry*. Cambridge: The Royal Society of Chemistry.
9. Ratnayake, W.S., & Jackson, D.S., (2007). A new insight into the gelatinization process of native starches. *Carbohydrate Polymers 67*, 511-529.
10. Ratnayake, W.S., & Jackson, D.S., (2009). Starch Gelatinization. *Advances in Food and Nutrition Research, 55*, 221-268. Elsevier Inc.
11. Schwan, H.P., (1957). Electrical properties of tissue and cell suspensions. *Advances in Biological and Medical Physics 5*, 147-209.
12. Trainito, C., (2015). *Study of cell membrane permeabilization induced by pulsed electric field – electrical modeling and characterization on biochip* [PhD Thesis]. University of Paris-Saclay, 184 pp.

13. Tsong, T.Y., & Su, Z.–D., (1999). Biological effects of electric shock and heat denaturation and oxidation of molecules, membranes, and cellular functions, *Annals New York Academy of Sciences 888*, 211-232.
14. Vilgis T.A. (2015). Soft matter food physics-the physics of food and cooking. *Reports on Progress in Physics 78*, 124602.
15. Vorobiev, E., & Lebovka, N., (2010). Enhanced extraction from solid foods and biosuspensions by pulsed electric energy. *Food Engineering Reviews 2*, 95-108.
16. Xu, C., & Li, Y., (2014). Development of carrot parenchyma softening during heating detected in vivo by dynamic mechanical analysis. *Food Control 44*, 214-219.

Corresponding author:
Prof. RNDr .Ing. Jiří Blahovec, DrSc., Department of Physics, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6, Prague, 16521, Czech Republic, phone: +420 22438 4281, e-mail: blahovec@tf.czu.cz