Dielectric impedance monitoring of heat pump drying of apple slices

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Abstract. Heat pumps have been known to be energy efficient when used in conjunction with drying operations. The principal advantages of heat pump dryers (HPD) emerged from the ability of heat pumps to recover energy from the exhaust as well as their ability to control the drying gas temperature and humidity. It is a low temperature (40-45°C) drying system, which can preserve the nutrition parameters of the raw material, but can produce a dried product, with high level of microbiological and shelf-life stability and safety. The apple slices were dried for five hours, till equilibrium dry content. The received product has low moisture (about 85 % dry base) which is good for longer shelf-life. Dielectric parameters (between 20Hz and 10MHz), volume and weight of the dried apple slices were investigated in every hour. The aim of the experiment series was to see, if the method of dielectric spectroscopy is useful to follow the drying process. To analyse the data in function of drying time non-linear (sigmoid) regression was used and linear correlation matrix was created between the measured parameters. The highest correlations are marked in the tables.

Keywords:
impedance parameters, non-linear regression, drying trends, correlation matrix, gentle drying,

INTRODUCTION

A tendency in the food industry is the attempt for reducing the cost of water and energy to the development of processes that use significantly less of these resources and generate smaller amount of waste (Lee and Okos, 2011). The application of heat pump technology allows the production of high quality products based on better heat and energy efficiency, without damage to the environment, reduce the production cost and power consumption (Pereira and Vicente, 2010). With appropriate choice of temperature-time variation, it is possible to reduce the overall colour change while maintaining high drying rates (Chua and others 2000a, b). The endpoint of the drying is the “equilibrium moisture content”. The moisture content remaining in a dry material, when the drying rate drops to zero at specified conditions of the drying medium is called the equilibrium moisture content. It is in equilibrium with the vapour contained in the drying gas and its magnitude is a function of the structure and type of the subject food and of the prevailing drying conditions. The equilibrium moisture values predicted by static and dynamic moisture sorption do not always agree over the whole range of relative humidity of the drying air. The drying of the fruits requires energy for removing of free water (evaporation or sublimation) and for removing of water associated with the food matrix (bound water).

Dielectric spectroscopy in a wide range of frequencies has been used earlier for monitoring the changing of the electric impedance of fruits and vegetables during drying (Zsivanovits, G. and E. Vozáry, 2011) and during long or short time controlled storage of apples and other fruits. The correlations between dielectric parameters and quality of melons were also analyzed by Wen-chuan Guo and others (2007). They reported relationships between fruit ingredients and dielectric parameters in high frequency range (from 10 MHz to 1.8 GHz). However, the prediction of soluble solid content by the dielectric properties was not as high as expected. Measurement of dielectric properties of agricultural material is essential for understanding their electrical behaviour (Nelson, 2008) level of mechanical damage (Al-Mahasneh and others, 2007) and also for the development of indirect nondestructive methods for determining their physical characteristics, including moisture content and bulk density. Venkatesh and others, (2004) found that corn samples chopped to different degrees showed a difference in dielectric response at similar bulk densities and moisture contents which indicated that some of the response was due to the chopping or size reduction. The dielectric properties of a food depend upon its composition. It is beneficial to conduct dielectric properties measurements for each product that is to undergo a dielectric heating process. Dielectric properties are with primary importance to evaluate the suitability and efficiency of heat pump drying of the products.

MATERIALS AND METHODS

Materials

Apples were washed with running water, peeled and cut into sticks 7*7*30 mm. The sticks were washed again and strained off.

Methods

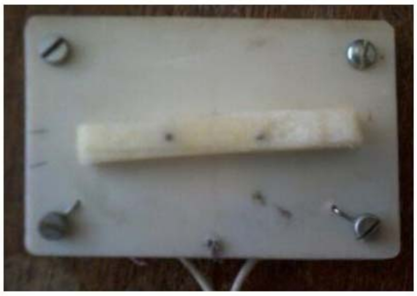
Drying was applied by highly energy-efficient and environmental protective heat pump drying (HPD). The applied drier was developed by FRDI – Plovdiv (Figure 1). The process was carried out at 45 ± 2°C and low relative humidity (average 10%) of the circulating air. The mass of apple sticks was measured during drying at every half an hour. The drying was finished when the mass was not changed already. The actual dry content was calculated based on the mass changes and original dry content of raw material, which was measured from samples at the beginning of the drying by standard methods.

Dielectric parameters of apple sticks (20 samples) were investigated in every hour. The stick samples were measured for volume changes by calliper, photographed by computer supported image analyzer system and weighed.

The impedance was measured by GW INSTEK 8110G precision LCR meter (Figure 2) in frequency range between 20 Hz – 10 MHz with stainless steel pin electrodes (gap 15 mm). Similar method and calculations were used earlier for monitoring the changing of the impedance during drying by Zsivanovits, G. and E. Vozáry (2011).

Figure 1
HPD configuration

GW INSTEK 8110G precision LCR meter



pin electrodes (gap 15 mm)

Figure 2
The applied instrument and stainless steel electrodes with an apple stick sample

Dielectric impedance and phase angle (θ_m) were used for the calculations in that experimental series. The real part (R_m), and imaginary part (X_m) of the measured impedance were calculated for monitoring the changing during the storage period:
If Z_m is a complex number, where:

$$Z_m = R_m + jX_m, \qquad (1)$$

and R_m is the real part of Z_m and:

$$R_m = |Z_m| \cdot \cos\theta_m , \qquad (2)$$

and X_m is the imaginary part of Z_m and:

$$X_m = |Z_m| \cdot |\sin\theta_m| \qquad (3)$$

The experimental values ($|Z_m|$ and θ_m) were averaged over measurements of twenty sticks in every hour (Vozary and others, 2002).

Based on the calculations the Nyqist plots (Liu, 2006) were drawn (Figure 3). The virtual R_m intercepts (left and right) with the frequency coordinates of them, and the max(X_m) points with the R_m and frequency coordinate of them were used to follow the changes during the drying. The received parameters may have connection with the dry content changes during the drying. The received data were processed statistically by non-linear (iteratively fitted sigmoid curve) regression in function of drying time. For the calculations Table Curve software was used. The used approximation formula was:

$$y=a+b/(1+\exp(-(x-c)/d)) \qquad (4)$$

The trend functions may useful to follow the drying process and to mark the endpoint (equilibrium water content) of it.

Linear correlation matrix was created between the received dimensional and dielectric data by Excel.

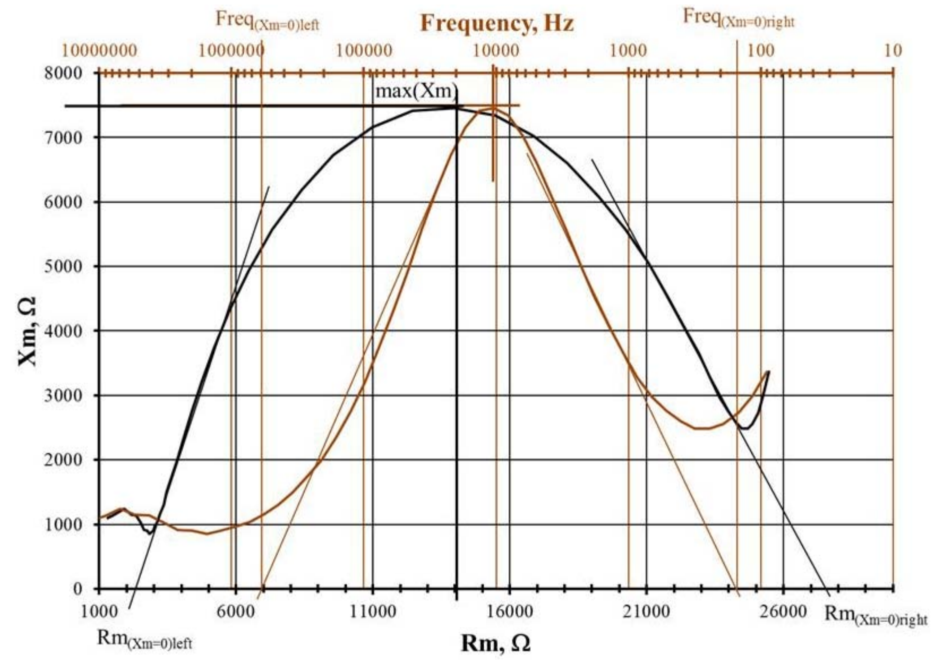


Figure 3
Nyqist plot of apple sticks before drying

RESULTS AND DISCUSSION

Results of mass volume and density investigation

During the drying time the mass and external dimensions of apple sticks were controlled in every hour. For further process of colour changes the sticks were pictured by computer supported digital image analysis system (Figure 4). The dimension changes can be followed by decreasing sigmoid functions (Figure 5 and

Table 1). That means, at the beginning of the drying the changes are faster, but later become slower and at the end of the process the parameters became near constant, after infinite time the calculated “a” constant should be the theoretical value. These near constant parts show the endpoint (equilibrium dry content) of that process method. Dryer product cannot received, from heat pump drying without increase the temperature. If the drying temperature increased, the quality of dried product and the energy efficiency of the process become worse. Based on the sigmoid trend all of the parameters had high correlation, parameters of density showed the highest correlation (r^2=0.9996), but it has the highest standard deviations for all of the points.

Table 1. Constants of non-linear (sigmoid) regression dimensional parameters and dry content

Parameters	Mass, g	Volume, mm^3	Density, kg/m^3	Dry content, %
A	0.228	786.74	294.44	0.12
B	3.834	45175.03	678.47	0.69
C	-0.734	-7.66	1.09	2.18
D	-1.026	-1.96	-0.62	0.68
r^2	0.9991	0.9713	0.9996	0.9971

Figure 4.
Apple sticks during drying

Based on the standard methods the refractometric dry content was 13.5 % and 14.25 % from gravimetric method. Based on the mass changes of the full dried item and the mass changes of the selected samples (20 sticks in every hour for the dielectric measurements), the dry content was calculated during the drying for every hour. The calculated dry content was changed up to 78-85 % during the drying. The received dry content values were also used for sigmoid trend calculations (Figure 5 and Table 1). The antioxidant activity (AOAC, 1990) was 15173.24 ± 1357.70 µmol/kgTE. These values were investigated just before drying.

Dielectric parameters

To analyse the parameters of the Nyqist plot nonlinear (sigmoid) regression calculations were used in function of drying time (Table 2). At the end of the drying the R_m values show slower increasing or near constant values. Maybe it is the result of the slower dimension changes. There are high correlations between the impedance parameters and drying time. The highest one is with R_m left (r^2 = 0.9980) (Figure 6).

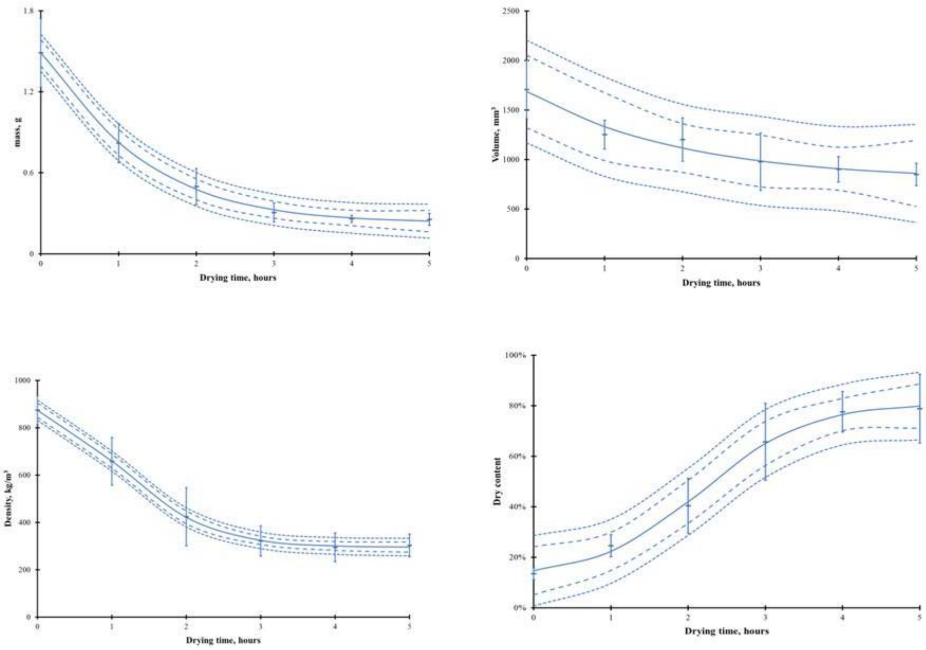


Figure 5.
Changes of external dimensions during the drying time
(mass, volume, density and dry content) with sigmoid trends

Table 2 Constants of non-linear (sigmoid) regression dielectric parameters

Parameters	R_m left kΩ	R_m Right kΩ	R_m max kΩ	Max(X_m) kΩ
a	3.83	51.41	17.83	-27.10
b	25.36	304.56	58.23	1328.36
c	3.36	3.39	2.68	4.73
d	0.37	0.66	0.90	1.17
r^2	0.9980	0.9880	0.9769	0.9907

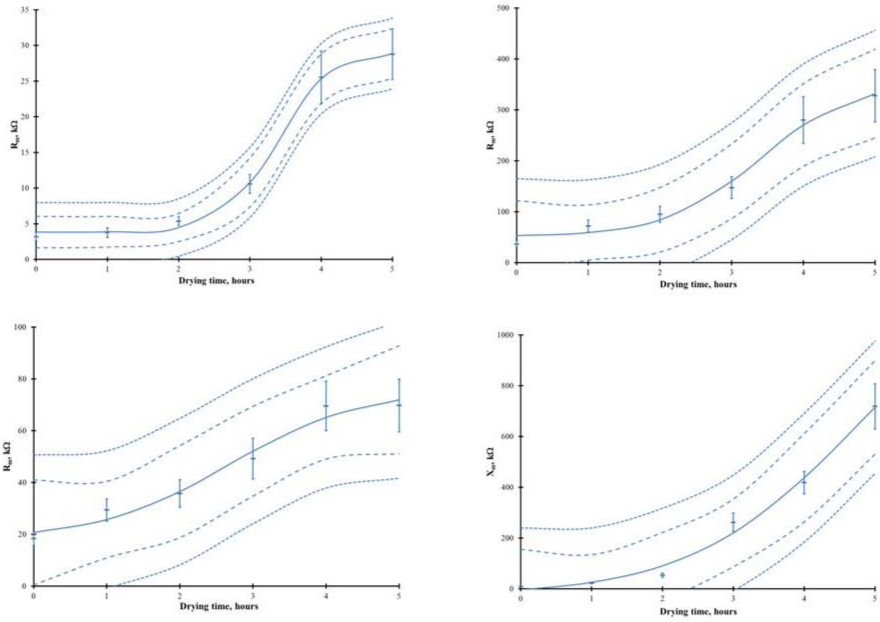


Figure 6
Dielectric impedance parameters in function of drying time with sigmoid trends

Table 3 Correlation matrix between the measured parameters

	Drying time, h	**Mass, g**	**Volume, mm^3**	**Density kg/m^3**	**LeftR_m0 kΩ**	**MaxX_m kΩ**	**R_m at MaxX_m kΩ**	**RightR_m0 kΩ**	**Highest corr.**
Mass	**-0.8884**	**1**							
Volume	**-0.9356**	**0.9769**	**1**						**Mass**
Density	**-0.9129**	**0.9871**	**0.9588**	**1**					**Mass**
LeftR_m0	***0.9292***	**-0.6866**	**-0.7852**	**-0.7256**	**1**				**Drying time**
MaxX_m	***0.9384***	**-0.6849**	**-0.7879**	**-0.7207**	**0.9604**	**1**			**Drying time**
R_m at MaxX_m	**-0.9716**	**0.9642**	**0.9699**	***0.9833***	**-0.8324**	**-0.8341**	**1**		**Density**
RightR_m0	***0.9636***	**-0.7595**	**-0.8469**	**-0.7887**	**0.9930**	**0.9681**	**-0.8837**	**1**	**Drying time**
Highest corr.	**RightR_m0**	**Density**	**R_m at MaxX_m**	**R_m at MaxX_m**	**RightR_m0**	**RightR_m0**			**Drying time**

To analyze the connections of measured dimensional and calculated dielectric parameters linear correlation matrix was created (Table 3). The correlation matrix shows high correlations between the dimensional changes and dielectric parameters. The highest correlations are marked in the table. The overall highest correlation was found between density and R_m at Maximum(X_m) (r=0.9833). This parameter has the highest correlation with all of the dimensional parameters as well.

CONCLUSIONS

As it is shown in the tables and on the figures the dielectric parameters are useful for monitoring the drying process. The high correlations between the dimensional and dielectrical parameters show the impedance parameters give information about the progress of drying.

FUTURE WORK

Next time we should repeat the work on more apples and with the examination of physico-chemical parameters during the drying process. The target of new experiments should be to look for connections between the quality parameters of dried products and the impedance parameters.

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