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Numerical analysis and experimental verification of the electrical impedance tomography method for monitoring of the packed-bed drying process

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Abstract

This paper presents a method for online determination the spatial distribution of the moisture content in material being dried. It might be essential for monitoring and optimal control of the drying processes. The proposed method utilizes electrical impedance tomography. As the exemplary material for experimental research the black chokeberry (Aronia melanocarpa) was used. The relationship between electrical impedance of chokeberry and its moisture content was determined for wide range of frequency (0.02–200 kHz). Experimental studies of the spatial distribution of the moisture content was performed in the cylindrical vessel equipped with 8-electrode circumferentially arranged. Voltage signal from the electrodes was acquired simultaneously using high-speed data acquisition module. Due to high impedance of the chokeberries, exceeding $10^9\,\Omega$ for dried matter, extraordinary instrumentation for stimulus sourcing and current measurement was necessary to be applied. On the other hand, raw chokeberries are characterized by several orders of magnitude lower impedance (10^3–$10^4\,\Omega$), especially for high frequency. Wide range of observed impedance was able to be measured owing to use of the voltage stimulation instead of the current stimulation. The image reconstruction problem was solved using iterative Gauss-Newton algorithm in the electrical impedance and diffuse optical tomography software package. The obtained results has shown satisfactory ability to localize insufficiently dried part of the material. It was proved, that strong dependence between moisture content in chokeberries and its impedance in whole frequency range provides more meaningful information than simple resistance or capacitance measurement. Prospect for the improvement of the spatial resolution of humidity imaging was also discussed.

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1 Introduction

Drying processes (e.g., agricultural crops processing) are known to be one of the most energy consuming processes. Therefore, any improvement of such processes may lead to significant reduce of energy consumption and thus ecologic as well as economic benefits. One of possibilities for optimizing the drying process is a proper process control strategy taking advantage of modern measurement techniques and instrumentation. The main purpose of this paper is study the prospect of application of the electrical impedance tomography as noninvasive measurement technique giving possibility of online monitoring of drying the agricultural crops. The use of such a method would allow a better control of a process, thus it may contribute in both improvement of the product quality as well as reducing the energy consumption. As the exemplary material for experimental research the black chokeberry (Aronia melanocarptinia, Photinia floribunda) [6] was used, but it appears possible to use this technique also for a range of other agricultural crops (e.g., currant, cranberry).

The term 'tomography' is common for all measurement and visualization methods that provide the information about spatial distribution of certain material properties within examined object, using measurements performed at the border of this object [5,7]. As a result of the measurement, the graphical representation of those properties distribution, can be achieved. Originally this technique was used in medicine but from early nineties of twentieth century the first engineering applications of tomography appeared leading to arise of the modern measurement technique known as 'process tomography'. The interest in the utilization of the electrical phenomena in tomography has contributed to advent of an electrical tomography which was relatively inexpensive in the application. The main advantages of all the tomographic methods may also include noninvasiveness. Depending on the electrical and magnetic properties of the examined object, different measurement methods are possible to be applied [10]:

1. Electrical impedance tomography (EIT) – the distribution of electrical conductivity is determined within the examined object.

2. Electrical capacitance tomography (ECT) – allows to determine the permittivity distribution in an area filled with dielectric.

3. Electromagnetic tomography (EMT) or magnetic induction tomography (MIT) – is used to determine the permeability distribution in the examined object.

In the literature one can find a few examples of the use of electrical tomographic methods for monitoring the drying processes [8,11], however, they relate mainly to applications in pharmacy and they use capacitance tomography instead of EIT as proposed in this paper.

2 Impedance spectrum of the chokeberry and its dependence on humidity

2.1 The method of examination

After the insertion of the conductive material (in this case chokeberry) between two electrodes, such a system can be regarded in simplification as a parallel combination of a resistor, R, and a capacitor, C, [2]. Since the reactance, X, of the capacitor shows the dependence of angular frequency, ω,

$$X = \frac{1}{\omega C}\,, \tag{1}$$

likewise, complex impedance of the circuit is function of angular frequency

$$Z(\omega) = \frac{RX^2}{R^2 + X^2} + j\frac{R^2 X}{R^2 + X^2}\,, \tag{2}$$

where j is the imaginary unit.

Using the absolute impedance, $|Z|$, and the phase angle, φ, complex impedance can be equivalently represented as

$$Z(\omega) = |Z|(\omega)\, e^{j\varphi(\omega)}\,. \tag{3}$$

For given measurement system both the absolute impedance and the phase angle are related to condition of a material being investigated (temperature, humidity) and that relationship might be obtained experimentally. On the other hand, knowledge about that relationship leads to the conclusion about the state of the material by measuring the above-mentioned values [2].

According to the literature data [6], initial humidity of fresh harvested chokeberry is typically 71.2–84.8%. The chokeberry frozen immediately after harvest was used for the experimental research. The material contains whole fruits, without any mechanical processing and damages. It is noteworthy, since in the case of processed chokeberry (eg., chopped or pressed) a peel of the fruit gets damaged and thus in such a situation the results described below cannot be reliable [3]. After defrosting and reaching room temperature a thin layer of water on the surface of the peel still existed – such a state of berries was assumed as the initial state (in this paper described as 'wet'). In a further step the chokeberry was dried in the open air at a temperature of 20 °C and air relative humidity 35–40%. The sample of material (approximately 75×10^{-5} m^3) was gathered periodically and the measurement of absolute impedance and phase angle was taken using procedure described below. Using the moisture analyzer, Radwag MAC 210, the humidity of the chokeberry sample was designated afterward. The measurement was taken for the chokeberry humidity range of 73.9–35.5%. In the case of yet lower water content (<20%) the impedance exceeded the measuring range of the instrument reaching more than 10^9 Ω.

The study was conducted in the measurement vessel, as detailed in Sec. 3.1, at a fixed temperature of 20 °C. In order of verification the procedure was repeated several times for each sample of the chokeberry. The repetition involved both in changing the measuring electrodes and the removal and reinsertion of the material into the area of the sensor. Each time the observed differences did not exceeded a few percent, and it is most likely the result of differences in the contact impedance between electrode and berries as well as between berries itself at different arrangements of the material. However, the phenomenon, which is important in practice, has been observed: after the insertion of the chokeberry into the measurement vessel, a gradual decrease in the impedance occurs. After approximately 30–50 min (depending on material humidity) the value of the impedance becomes steady. This phenomenon is the stronger the higher is the moisture content in the material and at the humidity lower than 30% the change of impedance is already insignificant.

The impedance of the chokeberry was measured using programmable LCR bridge meter Rhode-Schwarz Hameg HM 8118. This device allows to designate selected parameters of the circuit (in this case absolute impedance and phase angle) for 69 frequencies in the range of 0.02–200 kHz. Since the LCR bridge is equipped with RS232 communication interface, allowing to control the device using a computer, it was possible to automation the measurement procedure for the entire frequency range.

2.2 Experimental results

The results of the experimental research have shown a significant dependence of electrical properties of the chokeberry from its humidity. As could be expected, absolute impedance explicitly increases with decreasing the moisture content in chokeberry. This is due to a number of phenomena that occur during the drying of the fruit. The key importance here are: reducing the number of free ions due to the evaporation of the solvent as well as reducing the contact surface caused by changes in the structure of the peel [3]. Accordingly, the effect should be present for most of the agricultural crops being dried. The phase angle dependence of humidity of the chokeberry does not show such a clear trend. It is noteworthy, that the chokeberry with low moisture content shows characteristics similar to the dielectric. In this case, particularly at higher frequencies (10^4–10^5 Hz), the relationship between the phase angle and the moisture content of the material becomes meaningful. This gives the opportunity for use, at a later stage of the research, both resistive and capacitive properties of the system by proposing a dual modality tomography [4] method, combining EIT and ECT. The obtained results are shown on the graph (Fig. 1). Further research should obviously include carrying out measurements at different temperatures because its significant impact on the results might be expected.

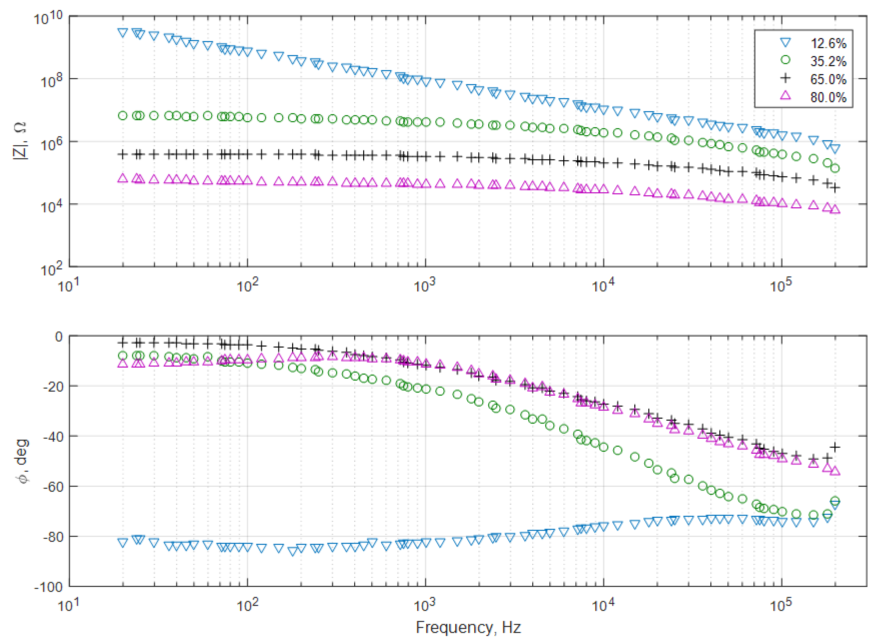

Figure 1. Impedance spectra of the chokeberry with different water content at 20 °C .

3 Imaging of the spatial distribution of moisture content in the chokeberry

3.1 The electrical impedance tomography test stand

A block diagram of the complete measurement system is shown in Fig. 2. The measurement vessel and the sensor of the tomograph were constructed using a polycarbonate pipe with internal diameter 0.11 m and height 0.08 m. Eight electrodes (size 0.075×0.03 m), made of cooper foil, was circumferentially arranged on the internal side of the vessel. The applied size of the electrodes, unusually large for EIT, results from the need to ensure similar contact impedance between the material and all electrodes.

To allow the sequential switching of the stimulating electrodes, the switching circuit (MUX) was designed and manufactured based on semiconductor multiplexer and reed relays. That subsystem was controlled by the digital outputs of data acquisition card. In most of implementations of an impedance tomography the alternating current (AC) stimulation (typically several milliamps) is used. This requires the use of voltage controlled current source (so-called 'current pump'), typically the Howland circuit [5]. However, current source should be characterized by significantly higher output impedance than the stimulated load. Due to the very high impedance of the chokeberry, it is virtually impossible to build the current source, which would allow the generation of stimulus signal in the required frequency range. These circumstances caused the necessity of apply in this research the voltage stimulation and accurate current measurement system. As the voltage source (SRC) the programmable signal generator, Agilent 33500B, was used. Since the current flowing through the chokeberry reaches low values (1–4 μA) it was necessary to develop the current-to-voltage converter characterized by high amplification factor. For that purpose the feedback converter circuit, based on operational amplifier with very low bias current, has been built [2]. This in turn allowed to reach the amplification factor 1 V/μA and the resolution of current measurement better than 0.2 nA.

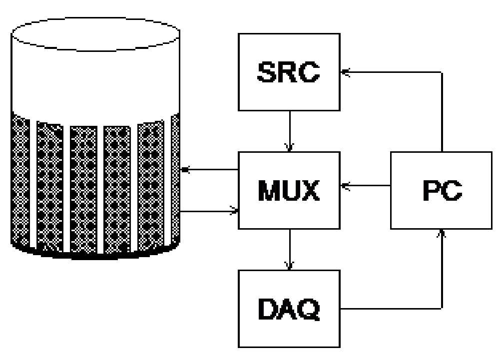

Figure 2. Block diagram of the EIT test stand.

The voltage on the electrodes was measured using a high-speed data acquisition card, National Instruments PCIe-6351. It is 16-channel, multifunction measurement card with accurate, 16-bit analog/digital converter with maximum sample rate of 1.25 MHz. The instruments measuring voltage is usually required to have the largest possible input impedance. Although the data acquisition card manufacturer reports that the the input resistance of the device is very large (> 1 GΩ), still the significant input capacitance (100 pF) results in a significant decrease in the input impedance in case of measurement of high frequency voltage. In order to reduce the impact of this effect on the achievable measurement accuracy, each input of data acquisition card was equipped with an additional buffering circuit based on a low noise operational amplifiers, OPA4228. This allowed for approximately 50 times decrease in the input capacitance of the measurement system. The complete stimulus switching and measurement system was controlled using a personal computer (PC) through the application written in the graphical programming environment LabVIEW [9].

3.2 Simulation analysis of projected image quality

Determination of the conductivity distribution in the cross-section of a sensor, based on the measured voltage, requires a two-step process. The aim of the first stage is to solve the forward problem, leading to designation of the transformation matrix of the measurement system. This step is based on the Laplace equation, which defines the distribution of electrical potential, φ, in the studied area with conductivity of the material, σ, [5]

$$\mathrm{div}\,(\sigma\,\mathrm{grad}\,\varphi) = 0\,. \tag{4}$$

The solution of Eq. (4) for the given measurement system is usually carried out with finite elements method. Introducing v as the vector of measured potentials at the border of the sensor leads to the designation of the transformation matrix $\mathbf{T}$, satisfying the relation

$$v = \mathbf{T} \cdot \sigma\,. \tag{5}$$

Reconstruction of the conductivity image is the second stage of the analysis of acquired data. The image is constructed by solving the inverse problem defined by

$$\sigma = \mathbf{T}^{-1} \cdot v\,. \tag{6}$$

However, matrix $\mathbf{T}$ is not the square one, thus it is not possible to use conventional methods of determining the inverse matrix. This problem has resulted in a number of algorithms for image reconstruction approximating the solution of the inverse problem [5,7].

Due to ill-conditioning of the inverse problem, the solution obtained may not reflect correctly the distribution of the analyzed characteristics in the area of the sensor. Feasibility of the correct imaging and the projected image quality should by verified using simulation studies. The use of specialized software, for example the electrical impedance tomography and diffuse optical tomography reconstruction software (EIDORS) [1], allows both the simulation test of impedance tomography systems, as well as the reconstruction of images based on experimental data. Reconstruction of the image in that software package is possible using a number of algorithms. A broad overview of the application of the software was presented, among others, in [5].

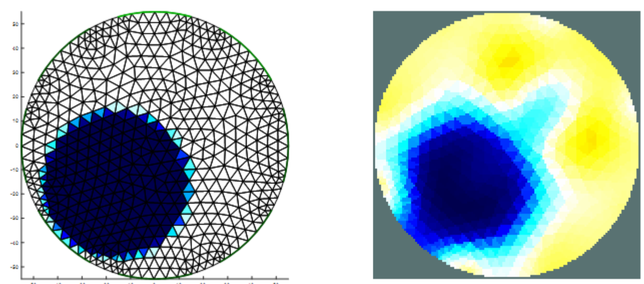

Figure 3. Finite element grid and image reconstructed using simulated data.

Simulation study was conducted for a situation in which inside the sensor, filled with the chokeberry, the area of higher humidity exists. That area had shape of circle of diameter 0.06 m (in real, 3D situation it would be cylinder), located as shown in Fig. 3 on the left side. The rest of the material had the same moisture content. Using the software the model of the measurement vessel, electrodes and distribution of material inside the vessel was created and the finite element grid was generated. In order to improve the accuracy of calculation the grid was thickened near the electrodes. That model was subsequently used to solve the forward problem and determining the potential distribution on the border of the area. In consequence, a simulated 'measurement set' was obtained which was used latterly to attempt the image reconstruction (Fig. 3, right side). For the solution of the inverse problem the iterative Gauss-Newton algorithm was applied [5]. As shown in the result achieved, identification of the area with higher humidity is correct. However, even in the case of simulation data, which is free from noise, material distribution nonuniformity or inaccuracies in the sensor design, the image reconstruction is imperfect. Outside the area of higher moisture content the image should be uniform, however, the mapping errors (artifacts) can be observed. This indicates a certain limitations of the image reconstruction algorithm.

3.3 Image reconstruction based on experimental data

Experimental verification of the simulation result was performed using the measurement system described in Sec. 3.1. The chokeberry was arranged inside the sensor as in the simulation studies (Fig. 3). Berries filling the majority of the volume of the sensor had a moisture content 35.2%, while inside the area marked by circle, moisture of the material was 69.5%. The large difference in humidity between areas stems from the need to investigate the obtainable imaging contrast. Determining the achievable imaging resolution of the moisture distribution in the material and attempting for improvement will be further stage of the study.

The voltage source was connect to each electrode in sequence (opposite method) and for every stimulation the voltage on every electrodes was measured. Therefore, complete measurement set comprises 64 voltage measurements. The measurement was taken for three values of stimulus voltage frequency: 100 Hz, 1 kHz, and 10 kHz. Similarly to simulation study, the iterative Gauss-Newton algorithm was applied to solve the inverse problem. The results of image reconstruction for each frequency are shown in Fig. 4.

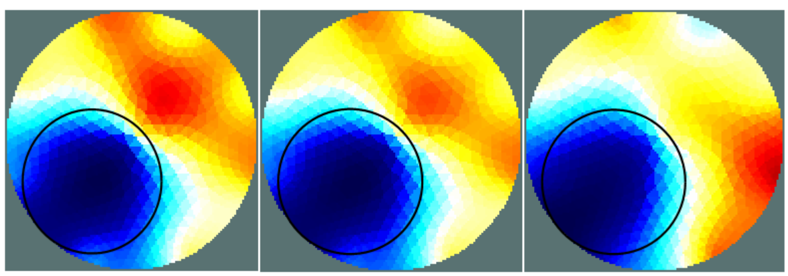

Figure 4. Reconstructed images for voltage stimulation of 100 Hz, 1 kHz, and 10 kHz, respectively.

As shown by the results obtained, irrespective of the frequency of the excitation voltage, the location of areas of high humidity can be considered correct. Since the obtained imaging accuracy was similar for all frequencies, at this stage of the research the use of quantitative indicators of the quality of imaging was not introduced. It can be seen that all of the reconstructed images are characterized by the artifacts of an intensity greater than in the simulation results. Presumably it indicates the need to introduce minor modifications to the measurement system. Nevertheless, the obtained results indicate a high potential usefulness of presented methods in a practical, non-invasive monitoring of drying processes in agriculture.

4 Conclusions

The study has shown a significant correlation between absolute impedance of the chokeberry and its water content in a wide frequency range. This indicates the possibility to use the impedance measurement to calculate the moisture content. In practice, the condition for the correct interpretation of the interdependence of impedance and humidity should take into account the temperature compensation – in this study it was not analyzed. Attention was drawn to the phenomenon of long-term stabilization of the measurement result after insertion of the chokeberry into the sensor. That phenomenon limits, but not exclude the application of presented method in the dryers with periodic mixing of the material. High impedance of the chokeberry requires an unusual approach to design of the measurement system of the electrical impedance tomography (EIT). Identification of the insufficiently dried material can be regarded as satisfactory despite the above mentioned issues. However, the artifacts appearing on images make difficulty in interpretation of the results, yet might be significantly reduced through minor modifications of the measurement system. This was showed in particular by the comparison of the simulation and experimental results. The accuracy achievable with other image reconstruction algorithms has not been studied, but the results acquired using impedance spectroscopy suggest that it will be possible to improve the imaging quality by taking into account both real and imaginary part of the complex impedance (especially at low moisture content in the material being dried).

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