Low frequency electric properties utilization in agriculture and food treatment

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ABSTRACT: Determination of electrical properties is utilized in a wide range of disciplines and industries. A brief compendium of agricultural materials and food electrical properties exploitation is presented in this paper. The measurement of electrical conductivity or resistivity can be utilized at investigation of cell membrane properties on microscopic level. Moreover the electrical conductivity have utilization at the salinity of soils and irrigation water determination. Biological material properties are determined from their leachates too. The conductivity measurement are applied for determination of various characteristics of agricultural materials and food, for example for determination of the frost sensitiveness, of chilling and freezing tolerance, of moisture content, of seeds germination, of mechanical stress, of pasteurization, of other properties of grains, seeds, meat, sugar, milk, wood, soil, fruit and vegetable, infected food, … The utilization of dielectric properties are also described; for example in agricultural materials and food quality sensing (moisture content, maturity of fruit, freshness of eggs, potential insect control in seeds, radio frequency heating, …). The classification of permittivity measurement techniques at the low frequencies is mentioned.

Keywords: electrical properties; moisture content; resistivity; conductivity; permittivity; impedance

Electrical properties are utilized in many areas of human activities. They have the biggest application at moisture content measurements. The research of moist material and development of measuring devices are absolutely necessary. The material investigation and moisture measuring using electromagnetic waves in wide spectrum serve for quality control and improvement in many branches like industry, forest and wood-working industry, civil engineering, agriculture, commerce, but also foodstuffs, semi-luxury foods, e.g. for quality detection of meat, fruits, coffee, etc.

Determination of moisture content is of vital interest to a wide range of disciplines and industries. The range of materials is also diverse and includes soil, cereals, dairy products and timber. However, beyond a measure of the mean moisture content, moisture content profiles are of interest. Distribution of moisture affects such crucial physical and biological phenomena as drying stresses in timber; moisture and heat transport, solute movement and biological organism behavior in soil; uniformity of dye absorption in textiles; and the quality of many food products. The capability to characterize moisture gradients or profiles is important for verification of the drying processes in the materials such as timber and textiles, or to characterize moisture content profiles in the soil due to drainage, surface evaporation, plant water uptake or capillarity. Hence a method for non-invasive, non-destructive measurement of moisture profiles would find wide application.

It is necessary to consider the change of the electric conductivity type at transition of the electric current through the biological material. The inside of the cell has the ionic conductivity. The electric current in a cellular membrane travels as displacement current. The density of the electric current i is defined as

$$i = \frac{1}{S}\,\frac{dQ}{d\tau}$$

where: Q – charge (C),
τ – time (s),
S – surface (m^2).

The relationship between the density of the current and electric field intensity is

$$\vec{i} = \sigma\,\vec{E} = -\,\sigma\,grad\,U$$

where: σ – electric conductivity (S/m),
$grad\,U$ – gradient of the electric voltage (V/m),
$\vec{E}$ – intensity of the electric field (V/m).

This equation is valid for electrolyte at low values of electric field intensity, too. Wien has shown in the year 1927, that the anomalies occur from the presented equation at intensity of 10^7 V/m.

BERLINER have been declared in 1973, that it is necessary to consider three components of direct electric current, when it is transiting trough the material: conduction component, which is invariable in the time, absorption component i_a, which is caused by polarization effects and we can describe it by a relation

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$$i_a = A\tau^{-k}$$

where: A – constant (A),
k – constant (1),

and if the time τ is equal 0, then i_a is equal 0 too.

Finally it is charging component i_n, which we can describe to look like flow trough the capacitor with a capacity C by relation

$$i_n = \frac{U}{R}\, e^{-\frac{\tau}{RC}}$$

where: R – resistance of the circuit (Ω),
U – source voltage (V).

If the time τ is approaching to 0, charging component is approaching to ratio U/R. The line current decreases with the time and its value is approaching to the conduction component. Electric measurements by direct current are very influenced by the polarization effects at high moisture content of the material.

If the current passing through the material is unsteady, for density of electric current is valid

$$i = \sigma E + \frac{d(\varepsilon E)}{d\tau}$$

where: ε – permittivity of material (F/m).

Complex value of current density is valid in the case of alternating electric field in the shape

$$\hat{i} = (\sigma + j\omega\varepsilon)\,\hat{E}$$

where: $\hat{E}$ – complex value of electric field intensity,
j – imaginary unit (1),
ω – angular frequency (1/s).

Permittivity of moist material must be considered to be complex. It has a real part ε' and imaginary part ε''

$$\hat{\varepsilon} = \varepsilon' - j\varepsilon'' = \varepsilon - j\,\frac{\sigma}{\omega} = \varepsilon\,(1 - jtg\delta_\varepsilon)$$

where: δ_ε – the loss angle (1) of the dielectric and

$$tg\delta_\varepsilon = \frac{\sigma}{\omega\varepsilon}$$

where: $tg\delta_\varepsilon$ – tangent of loss angle (1).

The maximum of dielectric losses is to be found around 20 GHz. This corresponds to a wavelength in air of about 15 mm and in many materials of about 5 mm to 10 mm. So a good measuring effect could be seen at this frequency, but only slight penetration of the material would be possible. That is why moisture measurement at very high frequencies is not useful for many applications. A lot of experiments had shown, that the well known ISM frequency 2.45 GHz is quite a good choice, because wavelength is about 10 times larger than at 20 GHz and dielectric losses are still high enough to be measured. ε_r'' is interpreted to include the energy losses in the dielectric arising from all dielectric relaxation mechanisms and ionic conduction. Materials such as agricultural material and foods generally have significant loss factors, and the dielectric properties are therefore dependent on both temperature and frequency as well as the chemical and physical characteristics of the material that include composition and density. The rapidly developing methods for measurement of material water content have their basis in an understanding of the propagation of electromagnetic waves in space or on a transmission line (TOPP, FERRÉ 2001).

Electric current travels look like a displacement current in the non-conductors. Maxwell entitled a quantity

$$\vec{i} = \varepsilon\,\frac{\partial\vec{E}}{\partial\tau}$$

as the density of displacement current. If the alternating currents are used at the measurements, that Maxwell relaxation constant has an important role. It is defined by equation

$$\tau_M = \frac{\varepsilon}{\sigma}$$

τ_M presents the time (s), after which the density of space charge falls e-times in the material. Maxwell relaxation constant is the criterion of material return to equilibrium state, so to a state without space charge. This time has values for a conductor 10^{-15} s to 10^{-13} s and for non-conductors achieves till 10^6 s.

CONDUCTIVITY MEASUREMENT

The precision of the most electrical apparatus is high at electrical properties measurement, measured biological materials bring into the measurement the biggest errors. Surrounding environs and errors of measurement devices have smaller effect on accuracy of the measurement. Electrical properties of the biological tissues have been of interest for many years. When studying the physical properties of tissue, it is necessary to consider its non-homogeneity from the macroscopic and microscopic points of view. When testing the electrical properties from the microscopic point of view, it is apparent that inside the of cell is conductive because there is conductivity of ion type in the content of the organic and inorganic matter solutions. The cell membranes are not conductors. From the macroscopic point of view, it is possible to regard the biological materials as non-homogeneous semi-conductors or dielectrics. The density and structural arrangement of the cells in them and the properties of each type of tissue influence the electrical properties of these materials. The characteristics of loose and porous materials are also influenced by the properties of air, which is trapped between the parts or in the pores, most especially its relative humidity and temperature. The deployment of the parts in the pack, the size of parts, gappiness, contact surface and bulk density also influence the electrical properties of loose materials. Among the influential factors for porous materials the following can be involved: size and distribution of pores, porosity and bulk density. Further factors are temperature of the material, but the most significant is the influence of the presence of water, its uneven deployment in the material, different binding energy in each water bond in the material and sorption properties (HLAVÁČOVÁ 2001).

Conductance of cell membrane

Electrical conductivity measurement can be used in many disciplines and industries. Determination of conductivity is of vital interest in the cell membrane techniques. For example the patch-clamp technique is utilized for electroporation of membrane during which resistance of the membrane returns to values in the GΩ range (MEISSNER 1998). Electroporation involves the formation of pores in the lipid phase of the membrane. These pores often last for dozens of minutes resulting in long-term electroporation, or they may last for only a few seconds yielding short-term electroporation. Electroporating pulses (1 V for 30 ms) were given in the vacuole-attached configuration resulting in a lowering of the patch resistance and allowing measurement of the tonoplast resistance.

VAN DUIJN et al. (1996) compared the properties of the inward rectifying potassium conductance in aleurone protoplasts isolated from dormant and non-dormant barley seeds. The ion fluxes are associated with dormancy-related plant growth regulator responses. Maximal conductance, voltage dependency of steady-state activation, activation and deactivation kinetics were studied in the whole-cell patch-clamp configuration. Activation and deactivation time courses were single exponential. The maximal conductance (corrected for cell size) in protoplasts from dormant seeds was much smaller (65%), and activation time constants were much larger in comparison with protoplasts from non-dormant seeds. The half-maximal activation potential was slightly more negative in protoplasts from dormant than non-dormant seeds.

HOLDAWAY-CLARKE et al. (1996) calculated the resistance of the membrane of the current-injected cell separately from the plasmodesmata resistance. Electrophysiological investigations of intercellular communication and membrane resistance in higher plants have been hampered by the difficulty in measuring these quantities independently. Uncertainty about the position of an electrode inserted into vacuolate tissue has further complicated such measurement. The presence of the plasmodesmata was fully incorporated into the electric-circuit model for the cell, which was used for the calculus.

Salinity of soils and irrigation water

In many causes the electrical conductivity measurement of irrigation water or soil is utilized to obtain fruit yield and quality. The salt stress is one of the main problems for deciding fertilization and irrigation policies. For example PALMA et al. (1999) found out that increased salinity decreases tomato fruit production, and fruits become blotchy and cracked.

MALICKI and WALCZAK (1999) used bulk electrical conductivity and permittivity measurement for evaluation of soil salinity. They determined the salinity index x_s, which can be calculated from two variables i.e. bulk electric conductivity σ and permittivity ε. The partial derivative

$$x_s = \frac{\partial \sigma}{\partial \varepsilon}$$

appeared independent of the moisture content and directly proportional to soil salinity. The bulk electrical conductivity and permittivity can be read simultaneously from the same sensor by the time domain reflectometry.

URRESTARAZU and GARCIA (2000) utilized the model of electrical conductivity management in a recirculating nutrient solution applied in open and closed systems for hydroponically grown plants.

Properties of seed using their leachate

Biological material properties are determined from their leachates too. There were for example seeds or grain deterioration described in the paper of VERMA et al. (2001). The conductivity values of the seed leachates were recorded after different soaking periods. It was observed that as the aging period increased, conductivity values also increased. However, a significant increase in leaching was observed after 24 h of soaking period. Results also showed that the increase in conductivity values of the seed leachates at different soaking periods was related to initial degree of deterioration of the seed lots. The conductivity values of the seed leachates in 3-year-old seeds were high compared with those of one- and two-year-old seeds in all soaking periods in all lots.

COUTO et al. (1998) utilized this method for quantitative mechanical damage evaluation in soybeans. Two modifications on the electrical conductivity test methodology were made: the utilization of a new number of grains per volume of water; and the introduction of a stirring process. Samples of soybeans were damaged by cutting the grain at the cotyledon junction and by impact of a mass falling from different heights. The samples of varying levels of damage were soaked in distilled water and their electrical conductivities were measured over 160 min at intervals of 20 min. The results showed that at soaking times other than zero, the response of electrical conductivity due to variations in percentage of damage was linear or quadratic. The introduction of a stirring process reduced the time taken for the detection of low level damage of the samples to 20 min.

PANAYOTOV and ALADZADHZIAN (1999) utilized the resistivity and absorption spectra of leachates from soaked pepper seeds. The resistivity decreased with development of seeds. Authors recommended to use these results in seed production and to obtain data on the condition and the sowing quality of seeds.

Differences of the electrical conductivity, organic and inorganic constituents in leakage from aged and non-aged vegetable seeds were observed by MIN (1995). The exudates from aged seeds contained higher concentrations of K, total sugars and total amino acids than those from control seeds.

MAEZAWA and AKIMOTO (1996) utilized electrical conductivity to determine the characteristics of low-temperature sensitive vegetables. The electrical conductivity and electrolyte leakage at injured and non-injured sites of vegetables showing chilling injury were compared. The time course of changes in electrical conductivity followed that reflecting the extent of surface pitting. Electrical conductivities and electrolyte leakage at sites with surface pitting were always higher than those at non-pitted sites. It is suggested that electrical conductivity and electrolyte leakage should be considered as the indicators of chilling injury.

TSAROUHAS et al. (2000) suggested the method for rapid assessment of freezing resistance. The electrolyte leakage method detected injury in more levels of freezing stress (–3°C, –4°C, and –5°C) than the impedance (–4°C, and –5°C). MANLEY and HUMMEL (1996) compared the index of injury with tissue ionic conductance formulas for analyzing electrolyte leakage data from freeze-stressed cabbage tissues. These results support the use of a simpler method for analyzing electrolyte leakage data in studies of cabbage freezing tolerance.

DIAS and MARCOS-FILHO (1997) utilized the electrical conductivity tests for vigour of soybean seeds. PANOBIANCO et al. (1999) utilized the same method for determination of correlation between the electrical conductivity of soybean seed and seed coat lignin content. Seeds were tested for electrical conductivity using four replicates of 50 seeds per cultivar soaked in 75 ml of deionized water at 25°C for 24 hours. It was concluded that seed soaking electrical conductivity is influenced by the seed coat lignin content. The electrical conductance test can be used as a valuable tool in the screening process for lignin content during soybean breeding, as the lignin plays an important role in resistance to mechanical damage and thus is a component of seed quality.

Determination of agricultural materials and food properties

Electrical properties measurement are utilized for determination of various characteristics of agricultural materials and food (BLAHOVEC 1993). Frost sensitiveness, chilling and freezing tolerance were observed by NEEFS et al. (2000) for chicory roots. Decrease in electrical resistance was detected before frost damage became visible. Thus, measuring the electrical resistance of root tissue can be used to predict frost damage. The most distinct frost damage symptoms were "water soaking" and browning of the vascular bundles. MANCUSO (2000) investigated freezing tolerance in an olive tree. The occurrence of electrical resistance changes in the tissues of the olive trees exposed to low temperature suggests the use of this experimental procedure as a quick, easy and non-destructive tool to screen plant tissues for chilling tolerance. The strong dependence of the electrical resistance on low temperature and the critical temperature of around 10°C can yield interesting information about the lowest thermal limits for the continuation of normal physiological processes, and therefore about the adaptability of plants to particular environments. OKAMOTO et al. (2000) studied cold resistance in root and cane of own-root Kyoho grapevines using electrical conductivity and triphenyl tetrazolium chloride tests. These results indicated that roots can not resist temperatures of –4°C for a single night during winter.

The effects of postharvest chilling (4°C) for up to 3 weeks on melting-flesh and peach (*Prunus persica*) genotypes were investigated by BROVELLI et al. (1998). Melting-flesh fruits were more susceptible for developing mealiness (woolliness) than nonmelting-flesh fruits. Cell separation in mealy fruits was demonstrated by the release of mesocarp cells to an aqueous medium, allowing determination of woolliness severity. At a histological level, chilling caused expansion of the intercellular spaces in melting-flesh mesocarp tissues, but did not affect nonmelting-flesh fruits. A decrease in flesh electrical resistance after 1 week of chilling was observed in melting-flesh fruits. The electrical resistance increased in melting-flesh and nonmelting-flesh fruits following 2 and 3 weeks at 4°C. The electrical resistance also decreased with ripening of melting-flesh fruits, but did not change when nonmelting-flesh fruits ripened.

The electrical properties are used in determining the moisture content of solid materials and biological materials too. Recently for example, LEPPACK (1998) measured resistance in potato storage. The electrical measurements were carried out on the harvested potatoes on trailers during their admission into storage facilities and optimum moisture contents for storage were determined. Metal rods were inserted 50 cm deep into the up most layer and left for continuous measurement. Stored potatoes must be kept at the right temperature and moisture content through forced ventilation to avoid losses through rot. The system measures resistance at 2 points on the tuber's skin, the current flows more rapidly over a damp skin than a dry one. This provides a more accurate method of moisture content measurement within the potatoes.

Electrical resistivity measurement for cotton lint moisture sensing was utilized by BYLER (1998). The resistance varied with sample thickness as expected, but the resistivity did not vary with sample cross-sectional area. Relationships between sample moisture content with sample resistance and sample geometry were examined. Models were found which fit the data well; the residuals varied inversely with sample moisture content and sample circumference.

In many works the seed and grains properties determination are described. ALADHZADHZIAN and PANAYOTOV (1999) established a correlation between seeds germination and specific electrical resistance. They observed that the resistivity was the lowest and optical density was the highest in younger seeds. The standardization of the electrical conductivity test for

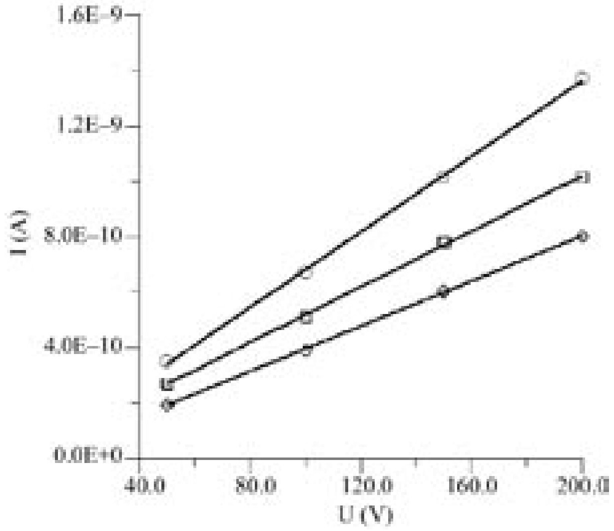

Fig. 1. The relationship between the current passing through the sample and the voltage, for sugar beet seeds, of cultivars Intera (○ filed seeds), Polina (□ coated seeds) and Remona (◊ encrusted seeds) at average moisture content of 9.39%

tree seed vigor was given by SORENSEN et al. (1997). VIEIRA et al. (1999) detected the correlation of electrical conductivity and other vigor tests with field emergence of soybean seedlings. Correlations between standard germination, accelerated aging and electrical conductivity and seedling field emergence were significant.

Our measurements were made with variously treated seeds (filed, coated and encrusted) of 9 sugar beet cultivars (HLAVÁČOVÁ et al. 2001). It was found that the electrical conductivity of seeds is affected by their surface treatment. The current passing through the pack of seed was measured. The highest current flowed through the sample of filed seeds and the lowest through encrusted seeds (Fig. 1). It follows that coating and encrusting of seeds increase their resistance. The mode of sugar beet seeds surface treatment could be dedicated by the measurements of their electric properties.

YU et al. (1995) utilized the electrical properties for selection of seeds with high viability, which is related to their amylase activity, proteinase activity and electrical conductance. They investigated the influence of high voltage electrostatic field separating effect on the biotic factors of rice, rape and sesame seeds during their sprouting period. When passed through a high-voltage electrostatic field, the rice, rape and sesame seeds were displaced towards the field. The separation between seeds of similar quality from the same height varied considerably and was related to the germination percentage of the seeds.

Electrical properties are utilized for determination of woody condition too. For example MOORE (1999) measured wood resistance. He utilized the combined use of the Resistograph and the Shigometer for the accurate mapping and diagnosis of the internal condition of woody support organs of trees. The Resistograph is an electrically driven drill which measures wood resistance, and is designed mainly for the diagnosis of wood defects in living trees but can also be used in timber. The Shigometer also has an electric drill but in addition has electrodes and an ohmmeter with which the electrical resistance is measured along the drilled hole; it is used on woody stems and roots. Their combined use provides acceptable results for most tree species and allows for a more accurate identification of the internal condition of roots and stems.

SILVA et al. (1999) proposed a new conductimetric sequential injection procedure for determination of chloride in milk. The use of a sequential injection system coupled to a dialysis camera permitted easy automation and improved process control over the parameters, giving high throughput analyses. An untreated sample of milk was injected with a standard reference solution in a carrier stream and dialyzed for the conductimetric chloride determination.

The conductivity measurement can be used to meat properties determination, for example BELLMER et al. (1999). The electrical conductivity is a critical parameter in the development of ohmic heating devices. They determined the electrical conductivity of ground beef samples using an ohmic heating device capable of expelling liquids. The resulting models indicate that conductivity is a strong function of both temperature and fat content. Changes in the conductivity were also determined for beef samples ground to three different particle sizes, and a comparison of their texture profiles was made. Texture profile analyses show that the hardness of cooked samples increases linearly with particle size.

Pork quality using parallel hypodermic needles were utilized by SWATLAND and UTTARO (1998). Four pairs of hypodermic needles were inserted around the axis of the muscle, with a view to making optical and electrical measurements simultaneously. An optical fiber was placed into each needle, and white light was focused into one needle of each pair. Scattered light transmitted to the other needles passed up optical fibers to the optical axis of a photometer. The needles were also connected to an apparatus for determining electrical measurements.

Electrical conductivity measurement of soil was utilized by LUND et al. (1999). Conductivity measurements of soil have been used to identify contrasting soil properties in the geological and environmental fields. The applications where electrical conductivity maps are proving useful in improving economic return to precision farming. FRIEDMAN (1998) simulated a potential error in determining soil salinity from measured apparent electrical conductivity. A simplified model of a randomly diluted and pore-size-distribution-decorated simple cubic lattice serves to describe the pore network of a saturated soil. It is assumed that only within each pore can the electrical conductance be represented by a sum of two conductors: the dissolved and the adsorbed ions acting in parallel. Using Monte Carlo lattice simulations, it was shown that the error due to the assumption of parallel mode on a bulk scale increases with increasing broadness of the pore-size distribution, decreasing connectivities, and increasing cation-exchange capacity.

Many of authors deal with the exploitation of electrical properties at mechanical stress determination in materials. DE ANDRADE et al. (1999) evaluated the mechanical damage to the bean seeds using electrical conductivity. Seeds of *Phaseolus vulgaris* were mechanically damaged at velocities of 10.0 m/s, 13.0 m/s or 16.5 m/s. Measurements of the electrical conductivity showed good correlation with the degree of mechanical damage. LEW (1996) examined interplay between the cell turgor pressure and the electrical properties of the cell: membrane potential, conductance, cell-to-cell coupling, and input resistance in root hairs. The pressure was directly modulated using a pressure probe or indirectly by changing the extracellular osmolarity.

Electrical heating utilized for food treatment was described by DEETH (1999). Current passage tube technology is a heating technology in which a stainless steel tube carrying a pumpable food product is connected to a low-voltage, high-amperage electrical power source and heated due to the resistance of the tube. The heat is transferred to the product flowing in the tube by conduction and convection. A unique feature of the technology is the constant temperature differential between the wall of the tube and the product along the length of the tube. This causes less chemical change in the product than conventional heat exchangers which, in the case of UHT processing of milk, results in less burn-on, and hence reduced cleaning and better flavor of the final product. The method has also been used for heat treatment of vanilla cream and on concentrated skim milk and milk fat.

The electrical measurements are utilized in many works to determination of fruit properties. For example GORDEEV (1998) developed an apparatus for investigating the electrical parameters of fruit tissue, viz. polarization capacity and conductivity. In order to develop a convenient instrument for determining the quality of batches of fruit and vegetables (apples, potatoes, etc.), a theoretical analysis was made of fruit tissue quality using an electrical model of a fruit. Experiments were conducted on several different apple cultivars to find the relationship between the electrical parameters of the tissue and quality indices, including the probability of occurrence of sound, diseased and damaged fruit for different storage periods. The instrument was developed for measuring active conductivity (7 kΩ–18 kΩ) and capacity (50 pF–1,500 pF) of any plant tissue at frequencies of 400 Hz and 250 kHz. The instrument can be used in the orchard or in the store, and it is calibrated by using a model fruit in the form of a parallel RC chain with R = 13 kΩ and C = 350 pF. MONTOYA et al. (1994) utilized a technique for measuring the electrical conductivity of intact fruits. They measured the electrical conductivity of avocado fruits during cold storage and ripening.

KEPPEL (1998) measured electrical resistance in the liquid phase. Measurement of *P*-value is a new method for the assessment of inner quality of foodstuffs (apples). *P*-value is calculated using pH value, redox potential and electrical resistance measured in the liquid phase.

Electrical properties utilization in food treatment are described in many works. In many papers milk electrical conductivity on line and clinical mastitis detection are mentioned. Most infections developed to clinical disease, and the majority were predicted by changes in the electrical conductivity of the foremilk. MARTIN et al. (1997) described the inactivation of *Escherichia coli* in skim milk by high intensity pulsed electric fields. Pulsed electric field treatment was used at 15°C. Pulsed electric field treatment in the continuous system inactivated more microorganisms than in the static system. Increasing the pulse duration increased *E. coli* inactivation. The inactivation of *E. coli* using pulsed electric field was more limited in skim milk than in a buffer solution exposed to similar treatment conditions of field intensity and number of pulses due to the complex composition of skim milk, its lower electrical resistivity and the presence of proteins.

JEYAMKONDAN et al. (1998) utilized the same method for pasteurization of liquid foods. High voltage pulses probably cause electro-polarization of the cell membranes, resulting in the inactivation of microorganisms. ŽITNÝ and ŠESTÁK (1996) described the direct ohmic heating in laminar flows in ducts. Knowledge of temperature distributions in laminar flow of power low liquids heated by electrical current (direct ohmic heating) enables to assess the effect of thermal treated of liquid food (rapid sterilization). There were found analytical solutions of temperature fields of arbitrary flow behavior index and suggested simple formulas for evaluation of temperature influence upon the electrical conductivity of heated liquids. CHEN and HUANG (1999) studied the electrical heating sterilizer for tissue culture tools. The thorough sterilization can isolate the path of microbial contamination. Two types of electric heating sterilizers were used to evaluate their performance. The results indicated that the power supply of a device can be controlled by the setting values of upper and lower temperature, and the internal temperature can be maintained with the sterilization ability.

The health state of some fruit can be observed on ground of their electrical properties. THAN et al. (1996) investigated the effect of pineapple blackheart on electrical resistance of pulp tissues. The electrical resistance of pulp from harvested pineapples with blackheart was lower than that of tissue from healthy pineapples. Resistance decreased with increase in disease severity. The measurement of the electrical resistance thus provides a rapid and convenient method of diagnosing the blackheart.

DIELECTRIC PROPERTIES MEASUREMENT

Determination of moisture content of porous media from measured values of bulk permittivity is based on the dominance of the high dielectric permittivity of liquid water relative to that of solids and of air. At present, most material moisture content determinations are made with electronic devices that measure an electrical property of the material that is dependent on its moisture content. The more practical measurement method appears to be that utilizing the dielectric properties of the material; more specifically its relative permittivity and loss factor. Several attempts have been made to measure the permittivity and moisture contents of granular materials using various techniques, which can be classified in different groups

– capacitance measurement,
– measurement of single kernel of grain,
– wave guide measurements,
– cavity measurements,
– open resonator,
– coaxial probe,
– non contact scattering measurements.

KUANG and NELSON (1998) described low-frequency dielectric properties of biological tissues, characterized by α- and β-dispersions. There are included ion activities, tissue microstructure, electrode polarization, which always cause problems at measurement.

Properties of agricultural materials and food by dielectric measurement

Permittivity of granular materials has been a subject of extensive study due to its inherent relationship with moisture content. Quality of agricultural products during harvesting, storage, processing, and trading is controlled by its moisture content. Various techniques have been developed to study the permittivity of granular materials. While measuring the permittivity of granular materials one ends up measuring the permittivity of the mixture of material with air, since in the bulk of granular materials there always exists air voids. The packing fraction of the powder is even less which also varies with pressure.

For the application of microwave heating processes, the dielectric properties of materials that re-involved must be known. The permittivities or dielectric properties of food materials are important in understanding the behavior of these materials when they are exposed to electromagnetic fields in the process of microwave cooking or in other processes involving radio-frequency (RF) or microwave dielectric heating. Understanding these properties is also important in quality sensing by various instruments. The most prominent example is instruments designed for rapidly sensing or measuring the moisture content of cereal grains and other food materials. However, food materials are so complex in their composition and in their dielectric behavior, that it is usually necessary to measure the permittivities under the particular conditions of interest to obtain reliable data.

THAKUR and HOLMES (2001) used a three dimensional vector finite element method (FEM) to model the permittivity of rice grain using the scattered far field radiation. Scattering of incident plane wave radiation is analysed to extract the permittivity of granular material. Some reduced parameters obtained from the scattered electric field show a very good correlation with the permittivity of materials (both dielectric constant and loss factor). Although the present analysis is based upon the permittivity of granular materials having dielectric constant between 1 and 7 and loss factor between 0.001 and 1.0, similar techniques could be developed for materials having different ranges of permittivity. They noted the generalized mixture equation to be applicable to the rice and air mixture

$$e^{\alpha\varepsilon_{eff}} = v_1 e^{\alpha\varepsilon_1} + (1 - v_1)\, e^{\alpha\varepsilon_2}$$

where: ε_1, ε_2, ε_{eff} – the permittivity of rice, air and their mixture, respectively,
v_1 – the volume fraction of the rice,
α – a constant which is –0.3363 for rice and air mixture.

KIM et al. (1997) determined the dielectric behavior of baked biscuit dough at radio frequencies for various conditions and to develop a prediction method for dielectric properties of the baked dough at radio frequency. This information is needed for RF post baking, one of the most successful applications of radio frequency heating.

A lot of methods based on the dielectric measurements are exploited at appraisal of quality of various fruits. Electric capacity measurement was utilized for watermelon quality determination by KATO (1997). The relationship between quality and density of watermelon (cv. Parnasus Queen) was investigated. A new electrical dry method for density sorting of spherical fruits, which measures the volume by electric capacity and mass by electronic balance, was proposed. A new packing house for sorting watermelons with cavities, porous flesh or low soluble solids content using this dry method was constructed and operated successfully. HARKER et al. (2000) used electrical impedance spectroscopy to assess changes in the electrical resistance of the apoplast and symplast in strawberry. Carbon dioxide treatments reduced the resistance of the apoplast (resistance at 50 Hz) below that of control fruits, but did not affect the resistance of the symplast (resistance at 1 MHz). This result suggests that concentrations of H^+ and HCO_3^- increased in the apoplast, although no change was detected in the symplast.

ARNOLD et al. (1998) described electrical impedance methods for assessing fruit quality. Methods were minimized or compensated the influence of interfacial impedances between electrodes and plant tissue, which occur when assessing fruit or vegetable quality by electrical impedance methods. Compensated 3-electrode techniques suitable for use with currently available impedance analyzers are presented. The techniques are illustrated by examples of their effectiveness at suppressing impedance artifacts with a novel tissue-probe and non-invasive measurement.

We measured the impedance and capacity of apricot flesh by LCR meter GoodWill 819 at the frequency from 20 Hz to 100 kHz.

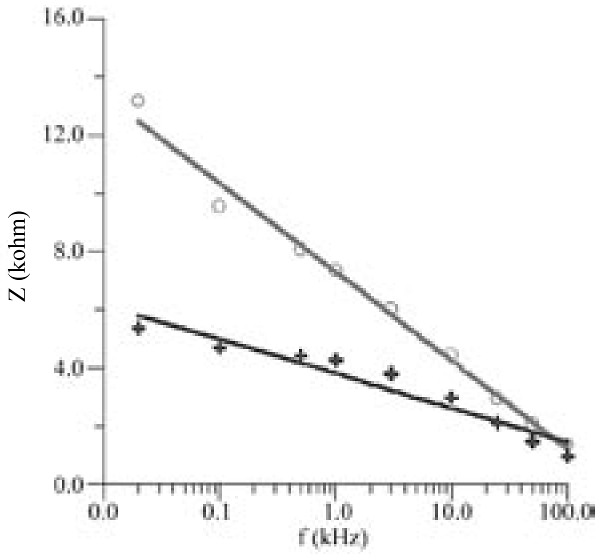

Fig. 2. The dependencies of the impedance on the frequency for an apricot number 4 of variety, Vesprima (+ less ripe side, o riper side)

The impedance of riper side is much higher at low frequencies compared to less ripe side. The values are nearly equivalent at high frequencies. The capacity values are on the contrary lower on riper side than on less ripe side. The difference is smaller at high frequency. The impedance decreased on values from 250 Ω till 900 Ω for decayed apricots, on the contrary the impedance of flesh intact with decay attained the values more than 13 kΩ. The decay of apricot flesh influences its electric conductivity, impedance and capacity, which are caused by damage of cell membranes (HLAVÁČOVÁ, HLAVÁČ 2003).

Dielectric methods are utilized at detection of mastitis in milk. For example NIJKAMP and POSTHUMA (1995) patented a device for measuring the complex impedance, such as the electrical conductance and/or capacitance of milk. It comprises a sampling chamber fitted with sensors in which the milk sample is received. The sensors are mounted in the chamber at equal heights, are parallel, and are elongated in shape. It is claimed that the device may be used to detect mastitis. POLYANSKIJ et al. (1997) utilized the capacitate dielectric method for determining mass proportion of lactose in solutions. A method was based on the phase measurements, a variant of capacitate dielectric method. The results of trials conducted with sucrose and lactose solutions are given. It is concluded that this method can be used for determining initial aqueous lactose solution and supersaturated lactose solution concentrations in the manufacture of refined lactose. SWANTEK et al. (1999) utilized electrical measurement to predict fat-free mass of pigs from 50 kg to 130 kg live weight. The bioelectrical impedance was evaluated. 4-terminal plethysmograph was used to measure resistance and reactance.

KAYA and FANG (1997) used dielectric constant and electrical conductivity for identification of contaminated soils. To investigate the usefulness of the preceding concept, the dielectric constant and electrical conductivity of kaolinite, bentonite, and a local soil are determined at various ion concentrations, organic liquids, and moisture content. Results show that both dielectric constant and electrical conductivity of soil-fluid system are mainly controlled by those of pore fluid.

Dielectric measurement of moisture content

At present, most grain moisture content determinations are made with electronic devices that measure an electrical property of the material that is dependent on its moisture content. The more practical measurement method appears to be that utilizing the dielectric properties of the grain; more specifically its relative permittivity and loss factor. Estimates of water content from electromagnetic measurements make use of the large relative permittivity of water compared to other material components. It is believed that a sensing device based on the capacitance principle of moisture estimation is more likely to meet the needs of ease of use, speed of measurements, and overall lower cost as compared to that of an equivalent microwave system. For in-field use there are five well-developed techniques operating between 10 MHz and 10 GHz in soil

– time domain reflectometry (TDR),
– capacitance,
– ground penetrating radar (GPR),
– airborne/satellite active radar,
– passive microwave methods.

Time domain reflectometry (TDR) and capacitance approaches use probes, which convey signal into the soil and thus can measure principally the upper one-meter depth. Ground penetrating radar (GPR) using non-invasive, transmitting and receiving antennae possesses the capability to measure to even greater depths without causing soil disturbance. Remote radar and passive microwave methods, operating generally above 1 GHz, derive their information from within a few cm of the ground surface.

There are many methods used for permittivity determination at microwave frequencies, including reflection measurements with short-circuited wave guides or coaxial lines containing the test samples, resonant cavity parameter measurement when loaded with a sample of the material, or transmission coefficient measurement for a large sample of material placed between two radiating elements in free space. During reflection coefficient measurement, grain density at the reflecting surface is most important, as all properties of the material at this plane determine the magnitude and the direction of the reflected wave.

SNELL et al. (2000) utilized electromagnetic measurement of the moisture content of chopped maize. The relationships between the moisture content of chopped maize (chopped by a self-propelled forage harvester) and fundamental electromagnetic parameters were determined, to aid in measurement of moisture content. Using an experimental SAIREM RF application unit at a frequency of 27.12 kHz, different parameters depending on the dielectric properties of the material were recorded, applying an electromagnetic field to chopped maize with different contents of dry matter.

BERBERT and STENNING (1999) presented that use of a capacitor to determine dielectric properties permits bulk density-independent measurement of moisture content of wheat seeds. Samples of wheat with moisture contents ranging from 11–22% and bulk densities ranging from 666 kg/m^3 to 873 kg/m^3 were used to derive density-independent equations to determine moisture content. The equation giving the best performance was capable of estimating moisture content of wheat seeds with standard errors of calibration and prediction of 0.4% and 0.5%, respectively. ANANYEV (2001) presented bulk density-independent equation too. The determination of grain moisture and bulk density using values of dielectric permittivity components measured on the fixed frequency was built on the mathematical solution of an inverse problem of bulk material dielectric measurements. There is established, that the function at f = const.

$$S = \frac{\varepsilon^{n}}{(\sqrt{\varepsilon'} - 1)^2}$$

depends only on moisture content does not depend on density, that it results their utilization for grain moisture meters.

TENG et al. (1999) described a new instrument for rapid measurement of moisture content of vegetable seeds. The characteristics and relationships between impedance-frequency and impedance-moisture of vegetable seeds were studied. Electrical conductivity was determined throughout the radio frequency range. A new method is presented together with a new instrument designed to measure the moisture content of vegetable seeds. Experimental results showed that the measuring range of the instrument is 5–20%, the accuracy being higher than 0.5%, and the uniformity better than 0.2%.

BUDIMAN et al. (2000) utilized a rapid measurement of moisture content of process cheese and cheese analog using low-field proton magnetic resonance. Proton magnetic resonance sensor was used for spin-echo amplitude ratio and CPMG spin-spin relaxation tests on cheese samples at room temperature and 63°C. The spin-echo amplitude ratio's were linearly correlated with moisture content at a given temperature.

BHATTACHARYA and TIWARI (1998) utilized proton NMR-relaxation for measurement of plant water status in some cereal crops. The relationship between leaf water proton-spin-lattice relaxation time, which can be measured by Nuclear Magnetic Resonance, and the conventional plant water status parameters, leaf moisture content, relative water content and leaf water potential, was investigated in barley and wheat grown in the field.

Time domain reflectometry (TDR) has become a standard method for water content measurement in soils. TDR method is based on the measurement of the velocity of electromagnetic pulse propagation in the investigated medium. This velocity depends on the medium dielectric constant. FERRÉ et al. (2001) utilized the sample area of time domain reflectometry probes in proximity to sharp dielectric permittivity boundaries. LAURENT and FERRARI (2001) discussed the applicability of TDS (Time Domain Spectroscopy) for quantifying under field conditions the dielectric behavior of wet porous materials like soils. The experimental set-up combining a commercially available TDR instrument and an adapted coaxial probe is presented. WALCZAK (2001) described the elaborated device based on TDR method, which enables to measure the moisture, electrical bulk conductivity and temperature simultaneously.

ETHERINGTON et al. (1998) used TDR to monitor the moisture content of grated coconut in real time and its effect on oil production. The moisture content of grated coconut affected the ease and efficiency of oil extraction.

CONCLUSIONS

Electrical properties of granular materials have been a subject of extensive study due to their inherent relationship with moisture content. Quality of agricultural products during harvesting, storage, processing, and trading is controlled by its moisture content. Various techniques have been developed to study the permittivity of granular materials. For the application of microwave heating processes, the dielectric properties of materials that re involved must be known. The dielectric properties of agricultural and food materials are important in understanding the behavior of these materials when they are exposed to electromagnetic fields in the process of microwave cooking or in other processes involving radio-frequency (RF) or microwave dielectric heating. Understanding these properties is also important in quality sensing by RF and microwave instruments. The most prominent example is instruments designed for rapidly sensing or measuring the moisture content of cereal grains and other food materials. Time domain reflectometry (TDR) has become a standard method for water content measurement in soils but also in other materials. TDR method is based on the measurement of the velocity of electromagnetic pulse propagation in the investigated medium. This velocity depends on the medium dielectric constant. The water content considerably modifies the dielectric constant of the capillary porous and cellular materials and therefore it has an impact on the velocity of electromagnetic wave propagation in them. The method offers rapid, nondestructive, automated measurement of water content in a wide range of soils with minimal soil-specific calibration. In addition, TDR probes are simple to construct, inexpensive, and allow for modification to tailor the measurement volume and spatial sensitivity of the instrument for specific measurement applications. Electric properties data on agricultural materials and foods have been compiled for reference in several publications. However, agricultural and food materials are so complex in their composition and in their dielectric behavior, that it is usually necessary to measure the electrical properties under the particular conditions of interest to obtain reliable data.

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Využitie nízkofrekvenčných elektrických vlastností v poľnohospodárstve a pri spracovaní potravín

ABSTRAKT: Určovanie elektrických vlastností je využiteľné v širokom intervale disciplín a priemyselných odvetví. V článku je uvedený stručný súhrn využitia elektrických vlastností poľnohospodárskych materiálov a potravín. Na mikroskopickej úrovni môže byť meranie elektrickej konduktivity alebo rezistivity použiteľné vo výskume vlastností bunkovej membrány. Ďalej má elektrická merná vodivosť využitie pri určovaní salinity pôdy a vody používanej na zavlažovanie. Vlastnosti biologických materiálov sú určované aj na základe vlastností z nich vylúhovaných roztokov. Meranie konduktivity je aplikovateľné pri zisťovaní rôznych charakteristík poľnohospodárskych materiálov a potravín, napríklad pri zisťovaní citlivosti na chlad, chladuvzdornosti a mrazuvzdornosti, obsahu vlhkosti, klíčivosti semien, mechanického napätia, pri pasterizácii a pri zisťovaní iných vlastností zŕn, semien, mäsa, cukru, mlieka, dreva, pôdy, ovocia a zeleniny, infikovaných potravín atď. V článku je tiež popísané využitie dielektrických vlastností; napríklad pri snímaní kvalitatívnych ukazovateľov poľnohospodárskych materiálov a potravín (obsah vlhkosti, zrelosť ovocia, čerstvosť vajec, potenciálna kontrola prítomnosti hmyzu v súbore semien, rádiofrekvenčný ohrev atď.). V práci je zmienené triedenie nízkofrekvenčných metód merania permitivity.

Kľúčové slová: elektrické vlastnosti; obsah vlhkosti; rezistivita; konduktivita; permitivita; impedancia

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