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Short communication

Dielectric properties of pineapple as function of temperature and water content

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Introduction

Microwave assisted processing is a new and growing field of interest for food industry (Tang *et al.*, 2002; Schubert & Regier, 2005). Many advantages (fast treatments, selective heating and so on) are obtainable by microwave heating due to its peculiar energy transfer that derives from a direct interaction between electromagnetic field and matter (Metaxas & Meredith, 1983). As foods are poor heat conductors, endogenous heat generation allows to overcome some difficulties that characterise conventional heating methods based on convective/conductive heat transfer phenomena (Barba, 2005; Botha *et al.*, 2012). The key-role in design, modelling and management of microwave assisted processes is played by the dielectric properties (or permittivity), which describe how microwaves interact with the irradiated matter. The dielectric behaviour of a substance is fully depicted by the single complex function known as permittivity and reported as relative entity:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \varepsilon' - i\varepsilon''(1)$$

The real part, ε', named dielectric constant, describes how much electromagnetic energy is stored into the material; the imaginary part, ε'', named loss factor, gives information about the electromagnetic energy dissipated as heat in the material (ε_0 is vacuum permittivity, 8.85 10^{-12} Fm^{-1}). Concisely, a material with a high loss factor is easily heated by microwave. Fundamental parameters in microwave heating, such as the volumetric power dissipated within irradiated material, $\dot{Q}_{mw}$, and the penetration depth, D_P, defined as the distance from the material surface at which the power drops to e^{-1} of its initial value, are strongly dependent on dielectric properties. Moreover, both $\dot{Q}_{mw}$ and D_P are easily calculated if dielectric properties are known. Permittivity of foodstuff is mainly function of frequency, temperature and water content. Furthermore, it depends on the material ionic composition and on the ash contents.

A considerable work was done on the investigations of the permittivity, in terms of their values (Sipahioglu & Barringer, 2003; Sosa-Morales *et al.*, 2010), as well as regarding their effects on the food quality (Barba *et al.*, 2008), and their impact on processes modelling (Malafronte *et al.*, 2012), being the applications not limited to food industries, but easily extendable to pharmaceutical issues, for example, in the treatment of excipients (Barba *et al.*, 2009c) and in the drying of pharmaceuticals for preparation of solid oral dosage forms (Barba *et al.*, 2009a,d). Moreover, knowledge of permittivity also allows to point out simple and effective methods to estimate food composition (Nelson, 2003; Kent *et al.*, 2005; Mckeown *et al.*, 2012) and state of foods, such as maturity (Nelson *et al.*, 1995) and freshness (Lougovois *et al.*, 2003).

Aims of this study are to acquire permittivity data of pineapple, which could be considered as a model food matrix, as it is representative of high moisture food, such as foods, fruits, vegetables, by varying the temperature and the water content and to fit the data with a simple and manageable mathematical model, providing a useful tool, which will meet all the requirements above listed. In particular, the final goal is to have a reliable prediction of dielectric properties and their changes for process management purposes (process optimisation), modelling applications (process simulation) and food properties estimation by reverse calculation (i.e. water content, freshness level).

Materials

Pineapple (*Ananas comosus*) fruits from Costa Rica (Gold Extra Sweet, *Del Monte*) were bought from a local greengrocer and stored at room conditions. Each pineapple was peeled and cut in cylinders of 3 cm diameter and 6–7 cm height.

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Methods

Dielectric spectroscopy of pineapple pulp was performed using the open-ended coaxial line method (suitable because the samples under investigation had high dissipative features), using a network analyzer (Agilent Technologies, Italia S.p.A., Cernusco s/N (MI), Italy ES 8753) equipped with an open-end coaxial probe (Agilent Technologies, 85070D). Air, distilled water and short circuit block were used as standards in calibration procedure. Investigated materials were subjected to dielectric spectroscopy in the frequency range 200 MHz–6 GHz; then the dielectric properties values at 915 MHz and at 2.45 GHz, frequencies of industrial interest, were extracted from the spectra. All the series of permittivity measurements were performed in triplicate.

To obtain the permittivity as a function of temperature, first of all, the fruit water content was assayed using a thermobalance (Ohaus, MB45), then the cut samples were rapidly heated using a quick microwave irradiation (in commercial microwave oven, *De Longhi*, *mod. Professional*) at maximum power of 1000 W for 30 s, then the permittivity values were measured during the natural cooling of the sample (which is confined in a sample holder to minimise water losses), recording in the meantime the sample temperature using three optical fibres sensors (FISO FOT-L, Fort Optical Fibers, data being gathered by the FISO UMI-8 conditioner). The use of more than one thermal sensor allowed the check that the temperature was homogeneous within the sample under investigation, and the use of the optical fibres ensured that the permittivity measurements were not affected by possible interferences with metallic temperature sensors. At the end of each temperature series measurements, sample water content was assayed once more, confirming that during the measures there was not any drying phenomenon allowed. Then, the use of multiple temperature sensors and the control of the humidity at the beginning and at the end of cooling process in several position in the samples (surface as well as internal), ensure that no appreciable gradients (of temperature or of water content) develop within the sample.

The protocol above described was firstly applied to the fresh fruit (initial moisture content $U_0 = 5.33 \pm 0.44$ kg water per kg dry substance, i.e. on dry basis, roughly 84% moisture content on wet basis). Therefore, many samples were partially dehydrated by natural convection at low temperature for long time (using a commercial oven, ISCO 9000, at 40 °C for variable time ranging from 4 to 72 h), to be sure that each sample had a homogeneous water content (the slow evaporation rate does not allow the development of moisture profiles inside the samples). Thus, three samples for each dehydration time were subjected to water content measurements, quickly heating and permittivity measurements during their cooling (meantime recording their temperatures). Finally, water content was assayed once more after the permittivity measurements, confirming that during the measure, no drying phenomena occurred.

Results and discussion

Following the protocol described in the previous section, permittivity values were obtained in a wide range of temperature and water content. In particular, the range of temperature covered during the measurements was from 100 °C to 25 °C; the range of water content covered was from 5.33 kg water/kg dry substance to 0.38 kg water/kg dry substance (from 84% to 28% on wet bases). For each couple of independent variables (T, U), the two spectra of ε' and ε'' (in the frequency range 0.2–6.0 GHz) were collected. Each measurement was replicated three times, and the average of the measurements was taken as the experimental data. Thus, each run gave four values: the dielectric constant, ε', and the loss factor, ε'', at the two frequencies of industrial interest, 915 MHz and 2.45 GHz. As a partial example of the data obtained, the experimental values of dielectric constant and loss factor at 2.45 GHz are reported in Fig. 1 (left graphs), as a contour plot with temperature, T and water content, U, both used as independent variables. The regions of the graph with the same tone of grey are characterised by the same value of dielectric constant (graphs above) or loss factor (graphs below). The numerical labels clarify the value of the two parameters. It is evident that the data show a complex, non-monotonous behaviour (e.g. the loss factor for a given temperature increases and decreases when the water content increases), therefore, simple rules, such as linear model, cannot describe them.

To get manageable mathematical tools, easily usable for modelling purposes (Acierno *et al.*, 2004; Barba *et al.*, 2009b), in this study, the proposed models were built with the simplest equations possible, which give reasonable predictions, keeping the number of fitting parameters at minimum. The simplest function able to account for non-monotonous behaviour is the quadratic one; using this latter indication two possible approaches are available. First, a sort of 'separation of dependencies' has been applied, obtaining:

$$\begin{aligned}\varepsilon(T,U) &= f(U)g(T)\\ &= (a_0 + a_1 U + a_2 U^2)(b_0 + b_1 T + b_2 T^2)\end{aligned} \quad (2)$$

In Eqn (2) six parameters $\{a_0, a_1, a_2, b_0, b_1, b_2\}$ are to be determined by fitting of experimental data. Another approach, which has been pursued, was to build a model accordingly with some sort of 'combination of dependencies':

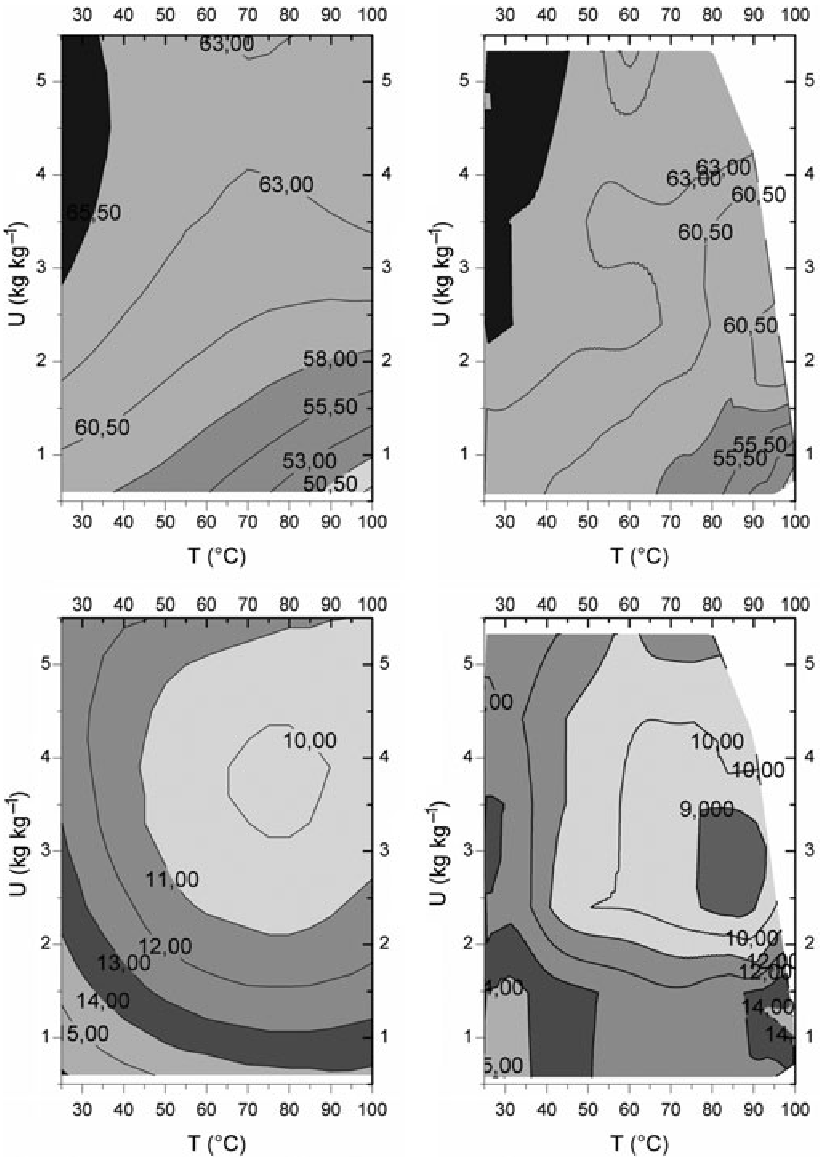

Figure 1 (Above) the contour plot of dielectric constant measured at 2.45 GHz, vs. temperature and water content. (Below) the contour plot of loss factor measured at 2.45 GHz, vs. temperature and water content. (On the right) the model calculations (Eqn 3), (on the left) the experimental data.

$$\epsilon(T,U) = b_0(T) + b_1(T)U + b_2(T)U^2 (3a)$$

where

$$b_0(T) = a_{0,0} + a_{0,1}T + a_{0,2}T^2$$

$$b_1(T) = a_{1,0} + a_{1,1}T + a_{1,2}T^2$$

$$b_2(T) = a_{2,0} + a_{2,1}T + a_{2,2}T^2 (3b)$$

In Eqn (3), nine parameters (the nine elements of the 3 x 3 matrix α) must be determined through a fitting procedure of experimental data. Thus, the two models were applied and the best fitting was achieved minimising the Sum of Square Errors function built comparing the model calculations and the experimental data for each point (221 experimental data points were available).

Figure 1 (right graphs) shows the calculations obtained by Eqn (3) for the dielectric constant (graph above) and for the loss factor (graph below). The complex experimental behaviour cannot be described exactly by such a simple model; however, it is evident that the model nicely captures all the trends of the experimental data, including, for example, the minimum shown by loss factor around $T = 80$ °C and $U = 4$ kg per kg.

Table 1 Parameter values for the use of fitting models. Above, the parameter values to be used with Eqn (2); below, the parameter values to be used with Eqn (3)

	Dielectric constant 0.915 GHz	Loss factor 0.915 GHz	Dielectric constant 2.45 GHz	Loss factor 2.45 GHz
a_0	3.57E+00	4.62E−02	3.90E+00	2.64E−01
a_1	2.16E−01	−1.18E−02	3.65E−01	−4.80E−02
a_2	−2.39E−02	1.45E−03	−4.36E−02	6.20E−03
b_0	1.80E+01	3.57E+02	1.49E+01	8.34E+01
b_1	−3.41E−02	2.51E+00	−1.87E−02	−6.11E−01
b_2	4.97E−05	−1.50E−02	−2.50E−05	3.79E−03
$a_{0,0}$	6.41E+01	8.58E+00	5.65E+01	1.78E+01
$a_{0,1}$	−2.29E−02	4.16E−01	8.46E−02	−2.23E−02
$a_{0,2}$	−1.22E−03	−3.22E−03	−2.01E−03	1.49E−06
$a_{1,0}$	4.76E+00	3.87E+00	7.36E+00	3.35E−01
$a_{1,1}$	−1.11E−01	−3.44E−01	−1.56E−01	−1.13E−01
$a_{1,2}$	1.33E−03	2.88E−03	1.74E−03	8.45E−04
$a_{2,0}$	−4.94E−01	−7.62E−01	−8.27E−01	−1.92E−01
$a_{2,1}$	1.16E−02	5.45E−02	1.71E−02	1.96E−02
$a_{2,2}$	−1.38E−04	−4.70E−04	−1.91E−04	−1.46E−04

Of course, the model based on the larger number of parameters shows the better description of the experimental data, e.g. SSE for ε' at 2.45 GHz is 2411 using Eqn (2) and it is 2297 using Eqn (3). Therefore, a statistical evaluation of the goodness of the models has been carried out following the Akaike Information Criterion (Akaike, 1974). According to this analysis, the decrease in the SSE using a model with a large number of parameters is useful if and only if it overcomes the increase in the number of parameters with respect to the use of a model with a limited number of parameters. In our analysis, we found that the use of the model with nine parameters (Eqn (3)) is worthwhile in the description of the dielectric constant, but the model with six parameters (Eqn 2) is enough in the description of the loss factor.

In conclusion, in this study, the permittivity of pineapple (which could be taken as a model food matrix) was measured as a function of temperature and water content of the samples. The data were fitted two simple models, both able to capture the non-monotonous behaviour of the dielectric constant and of the loss factor, for the two frequencies of industrial interest, 915 MHz and 2.45 GHz. The use of each one of the two models was advised on the basis of a statistical analysis. Summarising, Eqn (2) with the parameters reported above in Table 1 could be used in the modelling of the loss factor of pineapple as function of temperature and water content, whereas the use of Eqn (3) with the parameters summarised below in Table 1 is advised for the calculation of dielectric constant as function of temperature and water content. In principle, if the value of the temperature and of dielectric constant or the loss factor are known, the water content of the sample could be estimated reverse calculating it from Eqn (2) or Eqn (3).

The fitting models can be used both for the simulation of phenomena taking place during the microwave treatments of foodstuff, in which the permittivity plays a fundamental role (Malafronte *et al.*, 2012), and for the management of the drying process (Botha *et al.*, 2012), as well as for material characteristics indirect estimation (Mckeown *et al.*, 2012).

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