Dielectric properties of *Zea mays* kernels – studies for microwave power processing applications

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**Abstract.** Microwaves absorption in biological samples can be predicted by their specific dielectrical properties. In this paper, the dielectric properties ($\varepsilon'$ and $\varepsilon''$) of corn (*Zea mays*) kernels in the 500 MHz - 20 GHz frequencies range are presented. A short analysis of the microwaves absorption process is also presented, in correlation with the specific thermal properties of the samples, measured by simultaneous TGA-DSC method.

1. Introduction

Dielectric properties are characterized by the dielectric constant or permittivity, $\varepsilon'$, and are defined as the correlation factor between the electric induction $D$ and the electrical field $E$ applied to the material:

$$D = \varepsilon' E$$

(1)

For a variable electric field, $E = E_0 \exp^{-j\omega t}$, the permittivity has the expression [1, 2]:

$$\varepsilon^* = \varepsilon_o \left(\varepsilon' - j\varepsilon''\right) \text{ (F/m)}$$

(2)

where:

- $\varepsilon_o = 8.856 \times 10^{-12}$ F/m represents the dielectric properties of free space,
- $\varepsilon'$ is the degree of the induced dipolar variable-order (dispersion) by the electric field $E$ and
- $\varepsilon''$ represents the loss of electric energy (absorption) by normal conduction (electronic or ionic) and dipolar displacement or dielectric loss:

$$\varepsilon'' = \frac{\sigma}{\omega \varepsilon_o} + \varepsilon''_{\text{die}}$$

(3)

In equation (1) $\sigma$ is the material’s conductivity and $\omega = 2\pi f$, with $f$ the frequency of the electric field variations.

Usually the relative permittivity $\varepsilon_r$, a non-dimensional quantity, is used:

$$\varepsilon_r = \frac{\varepsilon^*}{\varepsilon_o} = \varepsilon' - j\varepsilon'' = \varepsilon' - j \left(\varepsilon''_{\text{die}} + \frac{\sigma}{\omega \varepsilon_o}\right)$$

(4)
together with the loss factor:

\[ \tan \delta = \frac{\varepsilon''}{\varepsilon'} \]  

(5)

The paper presents measurements of the \( \varepsilon' \) and \( \varepsilon'' \) values for corn (Zea mays) kernels in the 500 MHz to 20 GHz frequency range for the microwave field.

The material’s absorption \( \varepsilon'' \) or, more precisely, the loss factor, \( \tan \delta \), is the most important parameter in the microwave power processing of materials. The microwave power absorbed into the material is defined as [3]:

\[ P_a = \omega \varepsilon_0 \varepsilon' \tan \delta \varepsilon_0 E_i^2 = \omega \varepsilon_0 \varepsilon'' E_i^2 \quad \text{(W} / \text{m}^3) \]  

(6)

where \( E_i \) is the sample’s internal electric field and it depends on the incident microwave power \( P_o \) through the probe impedance \( Z_p \) in the microwave field, \( E_i^2 = P_o \cdot Z_p \).

If we consider that all the microwave power absorbed in the material during the period \( t \) of treatment is transformed into heat, \( P_a \cdot t = Q \), it is possible to evaluate the material’s temperature rising rate during microwave power thermal treatments:

\[ \frac{\Delta T}{\Delta t} = \frac{P_a}{m c} \]  

(7)

where \( m \) is the sample’s mass and \( c \) is the specific heat.

The corn kernel’s mass and heat flow variations versus temperature have been also investigated by TGA-DSC measurements, in order to determine the volatile content and the popping temperature of the seed.

2. Dielectric properties measurements

Dielectric properties measurements were performed with an Agilent N 5230A network analyzer and related accessories for dielectric properties measurements (Agilent 85070E Dielectric Probe Kit 200 MHz to 50 GHz). Two experimental configurations in the microwave field have been used, based on the reflected wave and cavity perturbation methods [2, 4].

![Figure 1. Dielectric relative permittivity \( \varepsilon' \) versus frequency, for various water contents in the sample (relative humidity, % HRU).](image)
are necessary. This method is very precise, even if it can be applied only at the resonance frequency of the cavity. The results obtained with the reflected wave method (figure 1, figure 2) have been verified by the perturbation method, at one frequency.

![Figure 2. Dielectric relative permittivity $\varepsilon''$ (loss) versus frequency, for various water contents in the sample (relative humidity, % HRU).](image)

For the reflected wave method, a single corn kernel was polished to obtain a minimum of 6 mm$^2$ of flat surface, where the coaxial microwave probe was applied. In the case of cavity perturbation method, a cylindrical shape having a volume of 5 mm$^3$ was cut out from the corn kernel and was introduced in the centre of a cylindrical cavity resonating at $f_{\text{probe}} = 9.5207$ GHz, in the TM$_{010}$ mode.

3. Thermal properties measurements on corn kernel
The samples (a regional variety of flint corn) were investigated by simultaneous TGA-DSC measurements, using a SDT Q600 analyzer (TA Instruments). The purge gas was argon, at a rate of 100 ml/min. The temperature and heat flow of the instrument were calibrated using alumel and nickel (Curie transition temperatures) and sapphire, respectively. The corn samples (about 5 mg) were weighed in open alumina pans. A single slice, cut from the kernel’s horny endosperm and placed at the bottom of the pan, was used for each measurement. An empty pan was used as reference. The experiments were carried out in a temperature range of 25-350°C at a heating rate of 10°C/min. The obtained data were analysed using the TA Universal Analysis Software Version 4.5A.

Figure 3 shows the TGA curve obtained for a corn kernel specimen. The mass loss starts very close to room temperature, and amounts to 13-14% weight, but the main thermal decomposition of the sample is initiated at around 270°C. The derivative weight loss curve indicates that the point at which the transition (popping) occurs is in very good agreement with the DSC results, as shown in figure 4. An endothermic peak was obtained, corresponding to the phase transition of the sample. As expected, the onset temperature at 225.09°C is higher than the one reported for popping corn (popcorn) variety [5], due to the specific experimental conditions (flint corn sample, measurement performed in inert gas flow, only a piece of the kernel, not the whole, was used).

4. Microwave absorption analysis in corn kernels
Microwave power absorption $P_a$ is difficult to be evaluated because of the probe impedance $Z_p$ in the microwave field, which depends not only on the material’s dielectric properties, but also on the sample’s volume and orientation in the incident wave or microwave coupling effect. Equation (6) is used in probing dielectric properties optimisation by adding supplementary moisture or other absorbent on the surface of the sample.
Figure 3. TGA curve recorded for a flint corn kernel sample, together with its calculated first derivative (in temperature).

Figure 4. Heat flow thermogram of flint corn sample (cutted from the horny endosperm) in inert atmosphere.

Considering a corn kernel mass of $m = 0.152$ g, a specific heat of $c = 2000$ J/Kg K and an effective power of $P_a = 2$ W transformed in heat, a rate of the temperature rising of $\Delta T/\Delta t = 5.02$ K/s is found. To obtain the popping transformation of the corn kernel, only a time interval $\Delta t = 40.8$ s (starting from room temperature) is necessary. The most important technological problem is to transfer the microwave power in the seed with a high rate.

5. Conclusions
The dielectric properties investigations indicate that the moisture content of the corn kernels has an important role in their dielectric properties in the frequencies range of 0.5 - 3 GHz. An additional 20% relative moisture increases with 200% the dispersion value $\varepsilon'$ and with 300% the absorption loss $\varepsilon''$. This result suggests the possibility of optimisation of the corn kernel treated in microwaves, by analysing it as a metamaterial with a high absorption in a specific frequency band [6].

Thermal analysis measurements confirmed that, for the investigated samples, the water content was of about 14% and the popping temperature is in the 150-250°C range [7, 8].

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