Dielectric properties of cereals at frequencies useful for processes with microwave heating

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Abstract Dielectric properties of barley, corn (white and yellow), sorghum, and wheat at microwave frequencies for heating purpose were analyzed. Properties were determined at 915, 2450 and 5800 MHz with the free space transmission method in the cereals at 20, 30, 40, 50 and 60 °C. ϵ' and ϵ'' of all the cereals decreased with increasing frequency. ϵ' slightly increased with temperature, while ϵ'' remained practically constant for all the cereals in the temperature range from 20 to 60 °C. Penetration depth decreased with increasing frequency for all the samples, and increased with increasing temperature at 915 MHz, except for barley. These results are useful for further microwave heating applications for the studies on cereals.

Keywords Dielectric properties · Cereals · Microwaves · Free space transmission line method · Penetration depth

Introduction

Cereals are important crops for both human and animal diets around the world. In Mexico, corn is a millenary crop of great importance. White corn is employed for tortilla

production and other artisanal foods. Yellow corn is produced more for chicken feeding, due to its high content of lutein and zeaxanthin, both yellow pigments that positively color the egg yolk; these pigments allow to have healthy vision (North Carolina Department of Agriculture and Consumer Services 2014). Sorghum is used for human diet, and for pigs and poultry feeding (Healy et al. 1994; Liu et al. 2013). Barley is employed extensively for beer brewing and other alcoholic beverages, while wheat is intended for flour, pastas and bakery industry. All these cereals and grains are often stored in silos and susceptible of insects or molds attacks. Dielectric heating (involving microwaves and radiofrequency) has been recognized as a good thermal alternative to control pests and molds in cereals and grains. Early studies using microwaves with this purposes in sorghum (More et al. 1992) and wheat (Warchalewski et al. 2000) has been reported. Recently, Yadav et al. (2014) reviewed the use of microwave treatments to prevent and control pests and fungal growth in cereals during storage, with multiple advantages, such as short treatment time, no hazardous effects on the kernels, safety for operators, greater energy efficiency, among others. However, for better understanding and application of microwaves, it is necessary to know the dielectric properties of the treated seed.

The dielectric properties of a material determine the interaction between that material and the applied electromagnetic field. They include the dielectric constant (ϵ') and the loss factor (ϵ''), the real and imaginary part of the permittivity, respectively (Jha et al. 2011). Moreover, penetration depth of the microwaves at the frequency and temperature of the study defines the layer depth of cereal and grains that must be subjected to assure the action of the treatment.

Dielectric properties of diverse grains and seeds in the microwave range have been reported by Nelson and Trabelsi

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(2011), in order to predict their moisture content or density (in the range of 5 to 15 GHz). Soltani and Alimardani (2014) also reported the dielectric properties of Iranian wheat to predict its moisture content. However, dielectric properties relevant to develop microwave heating protocols with disinfestation or decontamination purposes have not been published. The assigned microwave frequencies by the Federal Communications Commission for heating are 915, 2450, 5800 and 24,125 MHz (USDA 2000). Then, the objective of this work was to determine and analyze the dielectric properties and penetration depth of barley, corn, sorghum, and wheat at microwave frequencies and temperatures between 20 and 60 °C. Temperature was varied as it is well-known that dielectric properties are affected by temperature and because most of pest or molds may be killed/inactivated between 50 and 60 °C.

Materials and methods

Cereals

Samples of barley (*Hordeum vulgare* L.), corn -white and yellow- (*Zea mays* L.), sorghum (*Sorghum vulgare* L.), and wheat (*Triticum aestivum* L.) were acquired from producers in Cholula, Puebla, Mexico in the months of May–June 2014. Every lot of cereal was cleaned, removing strange matter or crashed/damaged seeds. To characterize the studied cereals, moisture content and bulk density were determined by triplicate. Moisture content was determined by gravimetric method according to official methods (AOAC 2000); while bulk density (Mohsenin 1986) was calculated by the relation of mass and volume taking 500 mL of sample.

Free-space transmission method

Transmission line method allows get the dielectric properties of a material as a part of a transmission line section (both reflection and transmission are measured) and is more accurate and sensitive than the probe method (Içier and Baysal 2004; Jha et al. 2011). Diverse reports have found the transmission method useful for dielectric properties measurement of different seeds in determined frequencies, such as corn (Trabelsi et al. 1998), rice and barley (Kim et al. 2002), wheat, soybean and corn (El Sabbagh et al. 2003), peanuts (Trabelsi et al. 2013), and beans (Torrealba-Meléndez et al. 2014).

Theory

Reflection and transmission from planar boundaries of air and a lossy medium - assuming that the incident

Fig. 1 Wave reflection and transmission scheme (adapted from Trabelsi et al. 1998)

wave is normal to the planar interface formed by the air and a slab of lossy material - is shown in Fig. 1. This slab is a container of thickness d and volume V filled with a non-magnetic particulate material at temperature T and moisture content M . For a homogeneous particulate material, M and T are assumed to be the same throughout the entire volume V , while bulk density ρ changes with the compaction of the material.

For the free space transmission method, it is important to obtain the reflection coefficient $\Gamma = E_r/E_i$ and the transmission coefficient $\tau = E_t/E_i$ at the interface, where E_i , E_r , and E_t are the electric field of the incident, reflected and transmitted waves, respectively. These coefficients are related to the dielectric properties of the material, which are dependent on composition and temperature. For a nonmagnetic material ($\mu = 0$) the reflection and transmission coefficients can be expressed as

$$\Gamma = \frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}} \quad (1)$$

$$\tau = e^{-\alpha d} e^{-j\beta d} \quad (2)$$

where α is the attenuation constant and β is the phase constant. The dielectric properties of the material can be

Fig. 2 Experimental scheme for the free space transmission method employed for the dielectric properties measurements of cereals

Table 1 Moisture content and bulk density of the studied cereals

Sample	Moisture content (% w.b.)	Bulk density (kg/m ³)
Barley	11.0 ± 0.0	790.5 ± 4.0
Corn (white)	9.2 ± 0.1	788.9 ± 7.4
Corn (yellow)	8.6 ± 0.0	761.3 ± 4.7
Sorghum	10.2 ± 0.1	756.9 ± 4.1
Wheat	11.2 ± 0.1	770.0 ± 3.9

calculated from attenuation and phase constants, by (Trabelsi et al. 1998):

$$\alpha = \omega \sqrt{\frac{\varepsilon'}{2} \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} - 1 \right]} \quad (3)$$

$$\beta = \omega \sqrt{\frac{\varepsilon'}{2} \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} + 1 \right]} \quad (4)$$

where ε' and ε'' are the dielectric constant and the loss factor of the material, respectively, and ω is the angular frequency. Thus, from eqs. 1–4, the dielectric constant and loss factor can be obtained by the measurements of the reflection coefficient Γ or transmission coefficient τ . In this work, the measurement of the transmission coefficient was employed, because the wave propagates from side to side of the container. Throughout routines using MATLAB software, ε' and ε'' were calculated

from expressions for a low loss material, with the condition $\varepsilon'' \ll \varepsilon'$ (Nyfors and Vainikainen 1989):

$$\varepsilon' = \left[1 + \frac{\Delta\phi\lambda_0}{360d} \right]^2 \quad (5)$$

$$\varepsilon'' \approx \left(\frac{|\Delta A|\lambda_0\sqrt{\varepsilon'}}{8.686\pi d} \right) \quad (6)$$

where $\Delta\phi$ is the angle of the transfer insertion function (degrees), λ_0 is the free-space wavelength (m), d is the thickness of the slab (m), and ΔA is the attenuation in the transmission due to the sample (dB).

Measurement system

Fig. 2 shows the scheme for the transmission coefficient measurement; the container full with the material was placed between two antennas. The attenuation in transmission ΔA (dB) due to the sample and the shift phase $\Delta\phi$ (degrees) of the transmission coefficient (τ) were obtained using a vector network analyzer (Sparq-3002E, Lecroy, USA). Subtraction of the reflection coefficient measured when the container is filled with them sample and the reflection coefficient measured when the container was empty was carried out to get the value for calculations. The employed antennas for frequencies of 915 and 2450 MHz were two broad monopole antennas, which operate from 0.8 to 3 GHz; here, antennas were placed in contact with the walls of the container (El Sabbagh et al. 2003). These antennas were described by Torrealba-Meléndez et al. (2015). For measurements at frequency of 5800 MHz,

Table 2 Dielectric properties of the studied cereals at different temperatures and assigned microwave frequencies (f)

Sample	f (MHz)	Dielectric constant					Loss factor				
		20 °C	30 °C	40 °C	50 °C	60 °C	20 °C	30 °C	40 °C	50 °C	60 °C
Barley	915	3.92 ± 0	3.92 ± 0	3.95 ± 0	3.87 ± 0.08	3.99 ± 0	1.21 ± 0	1.25 ± 0	1.19 ± 0	1.23 ± 0.03	1.22 ± 0
	2450	3.22 ± 0.01	3.07 ± 0.01	3.25 ± 0.09	2.74 ± 0.01	2.48 ± 0.02	0.64 ± 0	0.65 ± 0	0.68 ± 0	0.64 ± 0	0.64 ± 0
	5800	2.27 ± 0.0	2.47 ± 0	2.53 ± 0.03	2.55 ± 0	2.83 ± 0.01	0.58 ± 0	0.61 ± 0	0.63 ± 0	0.64 ± 0	0.71 ± 0
Corn (white)	915	3.81 ± 0	3.95 ± 0	4.01 ± 0	4.12 ± 0	4.23 ± 0	1.39 ± 0	1.33 ± 0	1.30 ± 0	1.27 ± 0	1.31 ± 0
	2450	2.87 ± 0.01	3.25 ± 0	2.91 ± 0.02	3.52 ± 0.02	2.57 ± 0.04	0.72 ± 0	0.72 ± 0	0.72 ± 0	0.77 ± 0	0.68 ± 0
	5800	2.46 ± 0.05	2.71 ± 0.01	2.68 ± 0.01	3.00 ± 0.01	3.32 ± 0.01	0.55 ± 0	0.60 ± 0	0.60 ± 0	0.70 ± 0	0.75 ± 0
Corn (yellow)	915	3.64 ± 0	3.58 ± 0.01	3.68 ± 0.0	3.92 ± 0	3.85 ± 0	1.33 ± 0	1.34 ± 0	1.30 ± 0	1.26 ± 0.04	1.27 ± 0
	2450	2.84 ± 0.02	2.71 ± 0.02	2.75 ± 0	2.84 ± 0.03	2.70 ± 0.01	0.68 ± 0	0.69 ± 0	0.69 ± 0	0.69 ± 0.01	0.69 ± 0
	5800	2.68 ± 0	2.89 ± 0	2.76 ± 0	2.93 ± 0.01	3.09 ± 0.01	0.62 ± 0	0.69 ± 0	0.64 ± 0	0.70 ± 0	0.72 ± 0
Sorghum	915	3.94 ± 0	3.94 ± 0	3.90 ± 0	4.08 ± 0	4.10 ± 0	1.38 ± 0	1.38 ± 0	1.31 ± 0	1.30 ± 0	1.32 ± 0
	2450	2.85 ± 0.01	2.90 ± 0.01	2.79 ± 0.06	2.81 ± 0.02	2.65 ± 0.02	0.72 ± 0	0.72 ± 0	0.72 ± 0	0.72 ± 0	0.74 ± 0
	5800	2.70 ± 0	2.81 ± 0	2.91 ± 0.02	3.0 ± 0	3.1 ± 0.02	0.66 ± 0	0.67 ± 0	0.68 ± 0	0.71 ± 0	0.71 ± 0
Wheat	915	3.66 ± 0	3.68 ± 0	3.75 ± 0	3.72 ± 0	3.79 ± 0	1.31 ± 0	1.33 ± 0	1.28 ± 0	1.29 ± 0	1.29 ± 0
	2450	2.92 ± 0.01	2.67 ± 0	3.02 ± 0.02	2.78 ± 0.01	2.63 ± 0.02	0.64 ± 0	0.65 ± 0	0.66 ± 0	0.65 ± 0	0.65 ± 0
	5800	2.79 ± 0.02	2.88 ± 0.01	3.08 ± 0.01	3.07 ± 0.01	3.08 ± 0.01	0.61 ± 0	0.64 ± 0	0.68 ± 0	0.68 ± 0	0.69 ± 0

two wide band Vivaldi antennas were employed, separated by 20 cm and operating from 3 to 10 GHz, as reported by Torrealba-Meléndez et al. (2014). The performance of the system was verified, with errors lower than 7 %.

Measurements of dielectric properties in cereals

For measurements at 915 and 2450 MHz, every cereal (around 6.6 kg) was placed in a cardboard cubic container (edge length of 20 cm). For measurements at 5800 MHz, the employed container (25 cm height, 11 cm width and 5 cm thickness) was filled with around 1.3 kg of every sample. Differences in dimensions and sample amount are related to the wave length at a determined frequency.

For the three target frequencies, the first measurement was carried out at 20 °C, then, the container with the cereal was warmed up in a microwave oven (1650 W, LG, Mexico) to increase the temperature to 30, 40, 50 or 60 °C. After warming, the cereal seeds were manually mixed and the temperature was measured with a T type thermocouple and a digital thermometer (DT-5808, WHDZ, China) within the container at different locations. Once the target temperature was verified, the container was taken within the anechoic chamber between the antennas, and the measurement was done with five replicates.

Determination of penetration depth

Penetration depth (d_p) is the distance (m) into a sample where the waves has dropped to $1/e$ (e is the Euler constant equal to 2.718), meaning 36.8 % of its transmitted value. d_p can be calculated based on the dielectric properties by the expression (von Hippel 1954):

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon' \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1 \right]}} \quad (7)$$

where c is the light speed in free space (3×10^8 m/s). The penetration depth, expressed in cm, was calculated after obtaining the dielectric properties of every cereal at the three frequencies and the five temperatures.

Statistic analysis

ANOVA tests and Tukey's pairwise comparisons were employed to analyze the results from dielectric properties for a particular cereal, using the software Minitab 17 (Minitab Inc., State College, PA), at a confidence level of 95 %.

Results and discussion

Characterization of cereals

Table 1 shows the moisture content and the bulk density of the cereals. From the studied samples, lower moisture content was determined in corn (9.2 and 8.6 % in white and yellow samples, respectively), followed by sorghum (10.2 %). Similar moisture content was found in barley and wheat (11 and 11.2 %, respectively). The moisture content of the cereals was checked before and after warming/measurements. Variations in the range of 0.16 to 0.33 % (w.b.) were observed; thus, no significant variations in the moisture content of cereals due to heating up were found ($p > 0.05$), without possible effect on the dielectric properties. Higher density for white corn (788.9 kg/m^3) was found in comparison with yellow corn

Fig. 3 Dielectric constant (ε') of yellow corn at different temperatures and frequencies measured with (a) monopole and (b) wide band Vivaldi antennas

(761.3 kg/m³), because the white grain is smaller in size than the yellow one.

The studied white corn accomplished with the established with the Mexican standard (NMX-FF-034/1-SCFI 2002) for handling and storage of white corn, which established maximum 14 % of moisture content and minimal density of 740 kg/m³ for tortilla and products of good commercial quality. Also, the yellow corn from this study met the Mexican standard (NMX-FF-034/2-SCFI 2003), which stands maximum 15 % of moisture content and minimal density of 740 kg/m³. Meanwhile, sorghum accomplished the moisture content (established as maximum 14 % by NMX-FF-037 1994) as well as barley (moisture content between 11 and 13.5 %, and density of 560–580 kg/m³ by NMX-FF-043-SCFI 2003). The studied sample of wheat is within the Mexican Standard for moisture content and density (marked as maximum 13 % and minimum 760 kg/m³ for moisture content and density, respectively, by NMX-FF-036NMX-

FF-036 1996). Additionally, the characteristics of barley, corn, sorghum and wheat are similar to those reported for the same cereals by Nelson and Trabelsi (2011) and for wheat reported by Soltani and Alimardani (2014).

Dielectric properties of cereals at microwave frequencies and selected temperatures

Dielectric properties of barley, corn (white and yellow), sorghum and wheat are depicted in Table 2. The standard deviation in most of measurements is zero, due to the experiments were conducted in an anechoic chamber, an insulated environment. Also, measurements took around 60 s and were taken in the same sample.

Both dielectric constant and loss factor values are low, due to low moisture content in cereals; ϵ' ranged between 2.27 to 4.23; while ϵ'' had values from 0.55 to 1.29 depending on cereal, frequency and temperature. These results are in agreement with those reported for barley (Kim et al. 2002); yellow corn (Trabelsi et al. 1997) and sorghum grain (Nelson and Trabelsi 2011). Generally, ϵ' and ϵ'' of all the studied cereals decreased with increasing frequency ($p < 0.05$). This observation was also reported by Guo et al. (2008) for chickpea flour, a low moist food too.

ϵ' slightly increased with temperature ($p > 0.05$) in the most cases. ϵ'' had different behavior: for frequency of 915 MHz, loss factor of the studied cereals decreased with temperature; at 2450 MHz, ϵ'' remained almost without variation, and at 5800 MHz, a little increase of loss factor respect to temperature there was observed. As example of this trend, Figs. 3 and

Fig. 4 Loss factor (ϵ'') of yellow corn at different temperatures and frequencies measured with (a) monopole and (b) wide band Vivaldi antennas

Table 3 Penetration depth (d_p) of the studied cereals at different temperatures and assigned microwave frequencies (f)

Sample	f (MHz)	d_p (cm)				
		20 °C	30 °C	40 °C	50 °C	60 °C
Barley	915	8.6 ± 0	8.4 ± 0	8.8 ± 0	8.4 ± 0.3	8.6 ± 0
	2450	5.4 ± 0	5.3 ± 0	5.1 ± 0	5.0 ± 0	4.9 ± 0
	5800	2.1 ± 0	2.1 ± 0	2.1 ± 0	2.1 ± 0	2.0 ± 0
Corn (white)	915	7.4 ± 0	7.9 ± 0	8.1 ± 0	8.4 ± 0	8.3 ± 0
	2450	4.6 ± 0	4.9 ± 0	4.6 ± 0.1	4.7 ± 0	4.6 ± 0
	5800	2.3 ± 0	2.3 ± 0	2.2 ± 0	2.0 ± 0	2.0 ± 0
Corn (yellow)	915	7.6 ± 0	7.5 ± 0	7.8 ± 0	8.3 ± 0.2	8.1 ± 0
	2450	4.8 ± 0	4.6 ± 0	4.7 ± 0	4.7 ± 0	4.7 ± 0
	5800	2.2 ± 0	2.0 ± 0	2.1 ± 0	2.0 ± 0	2.0 ± 0
Sorghum	915	7.6 ± 0	7.6 ± 0	7.9 ± 0	8.2 ± 0	8.1 ± 0
	2450	4.6 ± 0	4.6 ± 0	4.6 ± 0	4.6 ± 0	4.3 ± 0
	5800	2.1 ± 0	2.1 ± 0	2.1 ± 0	2.1 ± 0	2.1 ± 0
Wheat	915	7.7 ± 0	7.6 ± 0	7.9 ± 0	7.9 ± 0	8.0 ± 0
	2450	5.2 ± 0	4.9 ± 0	5.1 ± 0.1	5.1 ± 0	4.9 ± 0
	5800	2.2 ± 0	2.2 ± 0	2.1 ± 0	2.1 ± 0	2.1 ± 0

4 show the effect of temperature and frequency on the dielectric constant and loss factor of yellow corn, respectively. Temperature has a significant effect on dielectric properties; for multidispersion materials, dielectric properties may increase or decrease gradually due to combination of both relaxation and ionic conduction effects, obtaining a U-shape response in frequency (Komarov et al. 2005).

Penetration depth of microwaves in cereals

In all the studied cereals, penetration depth decreased with increased frequency ($p < 0.05$), as it is shown in Table 3. d_p ranged from 7.4 to 8.6 cm at 915 MHz and decreased to 4.3 and 5.4 cm for 2450 MHz, falling down even more for 5800 MHz with values between 2 and 2.3 cm for the studied cereals. Similar decreasing was reported by Guo et al. (2008) for penetration depth in chickpea flour in the frequency range from 1 to 1800 MHz. Deeper penetration is expected for lower frequencies, while higher frequencies will result in greater surface heating; dielectric properties of lossy materials vary with frequency, however, variation of penetration depth is not exactly $1/f$ (Komarov et al. 2005).

Among the studied samples, higher d_p was observed for barley at 915 and 2450 MHz. No differences in d_p were found between cereals at the frequency of 5800 MHz. Temperature affected in some cases the penetration depth in the samples at 915 MHz, for example in corn, sorghum and wheat, in which a slight increase in d_p with increasing temperature was achieved ($p < 0.05$). At 2450 and 5800 MHz, no effect of the temperature on d_p was observed for all the studied cereals ($p > 0.05$).

With the calculated depths, it is important to recommend thin layers of cereals to be treated with microwave heating, in order to ensure heating uniformity and adequate effectiveness against insect or mold control for these kernels.

Conclusion

The designed free space transmission line method was a good tool to get the dielectric properties of barley, corn, sorghum and wheat in the microwave range. Dielectric properties were affected by frequency, and at 915 MHz, also with effect of temperature. Penetration depth was useful to determine that, for further disinfection or mold control applications in the studied cereals, thin layers of maximum 8, 5 and 2 cm should be subjected to microwaves when frequencies of 915, 2450 or 5800 MHz be employed, respectively.

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