Journal of Food Engineering 155 (2015) 69–78

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Dielectric properties of green coconut water relevant to microwave processing: Effect of temperature and field frequency

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ARTICLE INFO

Article history:
Received 18 July 2014
Received in revised form 5 January 2015
Accepted 20 January 2015
Available online 29 January 2015

Keywords:
Dielectric properties
Microwave heating
Dielectric heating
Electrical conductivity
Penetration depth
Green coconut water

ABSTRACT

Dielectric properties (relative permittivity ε' and loss factor ε'') are key parameters for microwave heating of food products. In view of continuous microwave processing of green coconut water (GCW), dielectric properties and electric conductivity were determined by open-ended coaxial probe technique at temperatures between 0 and 90 °C and frequencies between 500 and 3000 MHz. Simulated solutions of salts and sugars from GCW were also tested to evaluate component contributions and interactions. At 915 MHz, ionic conduction plays an important role in microwave heating, while a balance between ionic and dipolar mechanisms was observed at 2450 MHz, depending on temperature. Sugars had a weak effect on polarization or loss. Component interaction reduced ε'' (approximately 12% at 915 MHz and 8% at 2450 MHz). It was possible to follow the change of the dielectric properties and the power penetration depth as the temperature raised and correlations were adjusted to model temperature dependence.

1. Introduction

Green coconut water (GCW) or tender coconut water is a popular tropical beverage rich in contents of minerals and sugars. It can be consumed directly from the immature coconuts (*Cocos nucifera*, L.) or processed to extend its shelf life by inactivation of undesirable enzymes and microorganisms. However, extension of the GCW shelf life without sensorial and nutrition value changes remains a technical challenge. The GCW is sterile and stable in the fruit but, after extraction, rapid discoloration and fermenting occurs because of microorganism contamination and the activity of enzymes polyphenol oxidase (PPO) and peroxidase (POD) (Campos et al., 1996; Matsui et al., 2008; Prades et al., 2012).

Thermal treatments such as pasteurization and sterilization, sometimes combined with additives, have been studied to preserve the GCW, varying degrees of success (Prades et al., 2012). Campos et al. (1996) reported that heating at 90 °C for 550 s with the addition of ascorbic acid (200 mg/L) was efficient for enzyme inactivation. Silva et al. (2003) processed bottled GCW for 10 min at 100 °C and Costa et al. (2005) used a hot fill method in glass bottles for 2 min at 90 °C. In both works, sodium metabisulphite (45 mg/L), sodium benzoate (124 mg/L) and ascorbic acid (1.3 mg/L) were used as preservatives. Citric acid and fructose were also added to standardize the pH, acidity and soluble solids content according to Brazilian regulation (MAPA, 2009). Chowdhury et al. (2005) processed canned pasteurized GCW at 121 °C for 30 min and bottled pasteurized GCW at 100 °C for 15 min. For stability, potassium metabisulphite (500 mg/kg) and citric acid were used as additives. Abreu and Faria (2007) used a UHT unit with plate heat exchangers to process GCW for 10 s at 139 °C with and aseptic filling. Ascorbic acid (200 mg/L) was required for physical–chemical stabilization of the product (color and peroxidase activity).

Prades et al. (2012), in a review about GCW preservation and processing, report that this is a very difficult product to preserve because of the thermal resistant enzymes and the color change induced by high temperatures. The authors conclude that emerging technologies should be investigated to develop processes that have less impact on the sensorial and nutritional quality of the GCW. In this context, microwave processing is an interesting processing alternative for GCW (Campos et al., 1996; Matsui et al., 2008; Zhu et al., 2012).

Liquid foods can be heated by electromagnetic waves (Decareau, 1985; Ryynänen, 1995), such as microwaves (wave frequency between 300 MHz and 300 GHz). Heating results from the ability of a dielectric material to convert part of the electromagnetic energy into thermal energy (Datta et al., 2005; Nelson and Datta, 2001). The heating of a food material by microwaves is the result of two main mechanisms: ionic conduction and dipolar rotation. In the first mechanism, dissolved ions move under the

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http://dx.doi.org/10.1016/j.jfoodeng.2015.01.011
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Nomenclature

a_i	polynomial coefficient, $i = 0, 1, 2, 3$ (–)
C'	component contribution on ε' (%)
C''	component contribution on ε'' (%)
c_0	speed of light in free space (m/s)
d_p	power penetration depth (m)
e	Euler's number, $e = 2.7183$ (–)
f	field frequency (Hz)
j	imaginary number, $j = \sqrt{-1}$ (–)
$p(T)$	temperature polynomial correlation (–)
R^2	coefficient of determination (–)
T	temperature (°C)
Tur	turbidity (%)
Tr	transmittance (%)
Greek letters	
$\hat{\varepsilon}$	relative complex permittivity (–)
ε'	relative electrical permittivity (–)
ε''	dielectric loss factor (–)
ε_0	electrical permittivity of the free space (F/m)
ε''_d	dielectric loss factor, dipolar contribution (–)
ε''_σ	dielectric loss factor, ionic contribution (–)
λ_0	electromagnetic wavelength in free space (m)
π	pi number, $\pi = 3.1416$ (–)
σ	electrical conductivity (S/m)
Subscripts	
interaction	component interaction in mixture
salts	salts from green coconut water
simulated	simulated green coconut water
sugars	sugars from green coconut water
water	distilled water
DW	distilled water
SGCW	simulated green coconut water
SGCW. Sal	solution of green coconut water salts
SGCW. Sug	solution of green coconut water sugars

influence of the alternating electric field and this motion leads to friction, resulting in conversion of kinetic energy into thermal energy. In the dipole rotation mechanism, thermal energy is generated by frictional interaction of the dipolar molecules that are continuously reorienting themselves to the alternating electric field (Muley and Boldor, 2013; Piyasena et al., 2003; Tewari, 2007).

When compared with conventional heating methods (conduction and convection), microwave heating provides a faster volumetric heating of the food product. In liquid flow, there is no overheating of the tube surface and, thus, less burnout. Moreover, the non-thermal effect of microwaves on GCW enzymes have been reported (Benlloch-Tinoco et al., 2014; Matsui et al., 2008). Consequently, the processing time can be shorter and the losses of temperature-sensitive attributes can be reduced (Decareau, 1985; Venkatesh and Raghavan, 2004). However, microwave penetration depth is limited and electric field distribution is uneven, which can give rise to non-uniform temperature distribution during the process, especially in food products with high unbound-water content. The free water molecules on the surface layer of the material efficiently converts the incident electromagnetic energy to thermal energy, reducing the penetration depth of the waves (Giese, 1992; Thostenson and Chou, 1999).

In order to design a processing unit with microwave heating for preserving liquid foods, it is necessary to determine the factors affecting the heating rate of the product (Giese, 1992). The dielectric properties are the key parameters for microwave heating, since they characterize the interaction between the electromagnetic waves and the medium providing information about heating performance and penetration depth (Datta et al., 2005; Ryynänen, 1995). Dielectric properties of materials are described in terms of the relative complex permittivity $\hat{\varepsilon}$:

$$\hat{\varepsilon} = \varepsilon' - j\varepsilon'' \qquad (1)$$

where the real part of $\hat{\varepsilon}$ is the relative electrical permittivity or dielectric constant (ε'), the imaginary part of $\hat{\varepsilon}$ is the dielectric loss factor (ε'') and $j = \sqrt{-1}$. The relative permittivity represents the ability of the material to polarize and to store electric energy in response to an applied electric field, while the dielectric loss factor is associated with energy dissipation as heat (Datta et al., 2005; Sosa-Morales et al., 2010). These parameters are affected by composition, temperature and electric field alternating frequency (Içier and Baysal, 2004).

Dielectric properties of several liquid food products have been determined for different frequency ranges and temperatures, including apple, pear, orange, grape and pineapple juices (Zhu et al., 2012), honey (Guo et al., 2011), milk, dairy products and soy beverages (Coronel et al., 2008), grape juice (Garcia et al., 2001), grapes and sugar solutions (Tulasidas et al., 1995) and milk (Kudra et al., 1992; Zhu et al., 2014). However, no information was found in the literature on the dielectric properties of GCW.

The objective of this work is to study the dielectric properties of GCW as affected by temperature (between 0 and 90 °C) and field frequency (between 500 and 3000 MHz) in view of the continuous thermal processing of this product using microwave heating. In order to evaluate the individual contribution of the GCW constituents (water, salts and sugars) on the dielectric properties, simulated solutions of GCW were also studied.

2. Materials and methods

2.1. Samples

Natural GCW was extracted from green coconuts (*Cocos nucifera L.*) purchased in a local market in São Paulo (Brazil). Coconut water was manually extracted from washed fruits, which were perforated with the hole-saw Fura-Coco (Keita, Guarulhos, Brazil). An 8 L batch of extracted water was mixed in a cooled tank, filtered through a paper filter (Packing Brasil, Louveira, Brazil) and frozen stored in a plasma freezer 349 FV (Fanem, São Paulo, Brazil) at −30 °C in sealed glass tubes prior to analyses. Natural coconut water was characterized by analysis of pH, acidity, total and soluble solids and turbidity, as described in Section 2.2.

To study the contribution of the GCW components (water, dissolved salts and dissolved sugars) on the dielectric properties, simulated GCW was prepared to mimic the average composition of fruits harvested with 7-month development (Brazilian green dwarf variety) according to Rosa and Abreu (2000). Simulated GCW was prepared by dissolving sugars and salts in 100 mL of distilled water (Matsui et al., 2007). The sugars used were: 2.4 g of fructose ($C_6H_{12}O_6$) Mm 180.16 g/mol, 2.38 g of D-glucose ($C_6H_{12}O_6$) Mm 180.16 g/mol, and 0.28 g of sucrose ($C_{12}H_{22}O_{11}$) Mm 342.30 g/mol. The salts used were: 62.26 mg of calcium chloride ($CaCl_2{\cdot}2H_2O$) Mm 147.02 g/mol, 42.7 mg of magnesium chloride ($MgCl_2{\cdot}6H_2O$) Mm 203.30 g/mol, 44 mg of monobasic potassium phosphate