Dielectric properties for selected wall material in the development of microwave-encapsulation-drying

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Abstract Dielectric properties study is important in understanding the interaction between materials within electromagnetic field. By knowing and understanding the dielectric properties of materials, an efficient and effective microwave heating process and products can be designed. In this study, the dielectric properties of several encapsulation wall materials were measured using open-ended coaxial probe method. This method was selected due to its simplicity and high accuracy. All materials exhibited similar behavior. The result inferred that β -cyclodextrin (BC), starch (S), Arabic (GA) and maltodextrin (M) with various dextrose equivalent exhibited effective encapsulation wall materials in microwave encapsulation-drying technique owing to loss tangent values which were higher than 0.1 at general application frequency of 2.45 GHz. Thus, these were found to be suitable as wall material to

encapsulate the selected core material in this microwave encapsulation-drying method. On contrary, sodium caseinate showed an ineffective wall material to be used in microwave encapsulation-drying. The differences in the values of dielectric constant, loss factor and loss tangent were found to be contributed by frequency, composition and bulk density.

Keywords Wall materials · Dielectric constant · Loss factor · Frequency · Bulk density

Introduction

The key parameter defining the interaction of materials within electromagnetic field is the dielectric properties (DP) of the materials. DP consists of dielectric constant (ϵ'), loss factor ϵ'' and loss tangent δ . The dielectric constant (ϵ') is the ability of a material to store energy when it is subjected to an electric field and influences the electric field distribution and the phase of waves travelling through the material (Sacilik et al. 2006). The loss factor ϵ'' , is the ability to dissipate energy in an applied electric field, influences both energy absorption and attenuation, and commonly results in heat generation (Mudgett 2007). The amount of thermal energy converted in the food is proportional to the value of the loss factor (Tang 2005).

The knowledge and understanding of the behavior of wall material DP in electromagnetic field will assist in selecting suitable wall material and designing faster and effective encapsulation process under microwave heating technique that can be used to add value to the product such as to extend the product shelf-life by means of encapsulation (Mohamad et al. 2017). Earlier, many potential applications of electromagnetic heating for foods have

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emerged and published, however the application of this for encapsulation process is limited because of the lack of dielectric properties data for wall materials used in encapsulation. Due to the potential development of microwave encapsulation-drying as a new, rapid and effective encapsulation technique, the aim of this study was to measure the DP of several common encapsulation wall materials at frequencies ranging from 200 MHz to 10 GHz.

Materials and methods

Materials

In this experiment, all samples used were purchased from Sigma Aldrich. The selected wall materials were gum Arabic (GA), carboxymethyl cellulose (CMC), β -cyclodextrin (BC), maltodextrin industrial grade (MI), maltodextrin (M) with various dextrose equivalent (DE) (DE 4–7, DE 13–14 and DE 16.5–19.5), starch (S) and sodium caseinate (SC). These wall materials are common wall materials used in encapsulation process with different interesting wall function properties, food grade and safe. GA able to create a strong protective film around oil droplets (Krishnan et al. 2005) and it have excellent emulsification properties (Dickinson 2003). CMC encapsulation could provide significant core retention during storage (Ma et al. 2013). BC is capable in forming inclusion complex or molecular encapsulation with material having molecular weight ranging from 200 to 800 g/mol and suitable for entrapment of poorly soluble, temperature sensitive, or chemically labile food bioactives including antimicrobials antioxidants, essential oils and flavors. Maltodextrin is suitable to be used as wall material for encapsulation because it is a good binder and stabilizer. It has good oxidative stability and the ability to control and modify solid and mouth feel without affecting sweetness or causing browning. SC is used because of its excellent emulsifying and film forming abilities.

Bulk density

The bulk density of the selected wall materials was measured using method described by Shafiur Rahman (2014).

Dielectric properties

The open-ended coaxial probe method is one of the popular techniques for measuring dielectric properties of materials due to its broad frequency bands, low sample disturbances,

easy to use, and it requires no special sample preparations (Wang et al. 2003). The measurement of dielectric properties of wall material was done by placing 5 grams of selected wall material in a glass petri dish. The wall material was spread evenly in the glass petri dish to ensure that the surface of the material was flat as the probe. Flat surface is critical to prevent air gap formation between the sample and probe, and within the sample as well. An air gap between probe and sample contributes to significant error in dielectric properties reading. Agilent E4991A impedance analyzer equipped with E4991A test fixture was used to perform the capacitance measurements of coaxial sample holder for frequency range of 200 MHz to 10 GHz. The measured capacitance values were converted by the dielectric properties system to dielectric constant (ϵ') and loss factor (ϵ'') using Eqs. (1) and (2). From Eq. (1), the dielectric constant is the ratio of capacitance value with sample in pF (C) to capacitance of the empty capacitor in pF (C_o) (Berbert et al. 2001).

$$\epsilon' = \frac{C}{C_o} \quad (1)$$

Meanwhile, according to Lawrence et al. (1998), the loss factor is defined as:

$$\epsilon'' = \frac{G - G_o}{2\pi f C_o} \quad (2)$$

where G is the conductance of the capacitor filled with sample in S, G_o is the conductance of the empty capacitor in S and f is the frequency in Hz.

The value of loss tangent ($\tan \delta$) is defined as the ratio of loss factor (ϵ'') to the dielectric constant (ϵ') and is expressed in the following Eq. (3) (Berbert et al. 2001):

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \quad (3)$$

The dielectric constant and loss factor values for each wall material were measured three times in frequency between 200 MHz and 10 GHz. These values were plotted in Excel for further analysis.

Results and discussion

Variation of dielectric constant of selected wall materials

Figure 1a shows the dielectric constants of BC, S, GA, CMC, MI, SC, M(DE 16.5–19.5), M(DE 13–14) and M(DE 4–7) measured at frequency of 200 MHz to 10 GHz. The dielectric constants for all these materials were below 4.

Fig. 1 Variation of dielectric constant (a), loss factor (b) and loss tangent (c) values for different wall materials as effect of frequency: ■, β -cyclodextrin (BC); ◆, starch (S); ▲, gum arabic (GA); ●, carboxymethyl cellulose (CMC); +, maltodextrin industrial grade (MI); *, maltodextrin (M) DE 16.5–19.5; ×, sodium caseinate (SC); ■, maltodextrin (M) DE 4–7; ■, maltodextrin (M) DE 13–14

All these materials were having low moisture content and food materials with low moisture content (< 4% wet basis) are generally poor electrical conductors when exposed to electromagnetic field.

The dielectric constants of the materials varied with the frequency. The ϵ' increased more at lower frequencies than

at higher frequencies and the ϵ' values decreased with increase in frequency. This was also observed in Sacilik et al. (2006). The important phenomenon contributing to the frequency dependence of the dielectric properties is the polarization of molecules arising from the orientation with the imposed electric field, which have permanent dipole moments (Venkatesh and Raghavan 2004). This results might be explained by the fact that, as there is no moisture content involved in this measurement, there are only possibilities of the dielectric constant reading is only based on the electronic and atomic polarization mechanism occur within the molecules (Ryynänen 1995).

The ϵ' values for all wall materials increased with an increment in frequency between 200 and 800 MHz. Between 800 MHz and 10 GHz, the values of ϵ' decreased with the decrement in dielectric with frequency occurs due to the phase lag between the dipole alignment and the dielectric field (Agilent Basic of Measuring the Dielectric Properties of Materials Application Note). Different rate of decrease in dielectric constant was observed for each wall material plausibly due to materials' bulk density and composition (Guo et al. 2008). Another factor that might possibly affect the dielectric properties of the materials is the physical structure of the material (Ryynänen 1995).

The molecular weight of the wall material has no effect on the magnitude of the ϵ' at different frequencies. The order of ϵ' curve of the wall materials was as followed: BC > S > GA > CMC > MI > M(DE 16.5–19.5) > M(DE 4–7) > SC > M(DE 13–14). It is important to highlight that the materials were separated in two well defined groups at 10 GHz frequency region. This might be contributed by oligosaccharide structure in BC, S and GA. The remaining wall materials (CMC, MI, M and SC) only contain linear and branch structures.

Variation of loss factor of selected wall materials

Figure 1b presents the variation of ϵ'' for the selected wall materials. All wall materials displayed similar behavior in ϵ'' variation with increase in frequency except for BC. In frequency region between 200 MHz and 10 GHz, it was observed that the values of ϵ'' for BC decreased from 0.59 to 0.35. On contrary, the ϵ'' values for the other wall materials increased with the increase in frequency in frequency region between 200 MHz and 4 GHz, then, the values decreased with increase in frequency in frequency region of 4–10 GHz. The following is the order of ϵ'' curve of the wall materials: BC > S > GA > CMC > MI > M(DE 16.5–19.5) > M(DE 4–7) > M(DE 13–14) > SC. This ϵ'' order is slightly different from the ϵ' order was

discussed above. This is plausibly due to the capability of energy dissipation which depends strongly on composition (Sosa-Morales et al. 2010) and density (Sacilik et al. 2006). One important observation was noticed in frequency region of 3–4 GHz where in this region, the wall materials seemed to be divided in three groups (Fig. 1b). The first group consists of BC, GA, S and CMC, followed by a group of M with different DE and the last group which only consists of SC, and SC which was the only protein-based wall material studied in this work.

The S and BC showed the higher loss factor because of smaller and finer particle size compare to others (Fig. 1b). This may be explained by the fact that the particle size also affected the loss factor; the lower the particles size the larger surface area to absorb energy which led to increase in loss factor.

Variation of loss tangent of selected wall materials

The variation of loss tangent values of the selected wall materials is shown in Fig. 1c. Loss tangent is also known as dissipation factor. Dissipation factor infers to the heating capability material under the electromagnetic field. Figure 1c shows the heating capability of each wall material studied. The pattern of variation for loss tangent with respect to frequency is similar to the loss factor plot. BC has the highest value of loss tangent followed by S, CMC, GA, M and lastly SC. These loss tangent values were obtained from the ratio of dielectric constant to dielectric loss (Eq. 2).

At 200 MHz, the loss tangent values for BC, S, GA and CMC were high. In the frequency region between 200 MHz and 1.5 GHz, the loss tangent values decreased with frequency. The values increased with frequency in the frequency region between 1.5 and 4 GHz. Then, the values again decreased with frequency in the frequency region between 4 and 10 GHz. It was found that the loss tangent values for all wall materials except for SC at 2.45 GHz were > 0.1 , which is the loss tangent of water at this frequency. It has been mentioned by Gabriel et al. (1998) that water is a useful dielectric heating material and it is the basis of the successful energy transfer in microwave in the food industry, and any material having a loss tangent value > 0.1 is an appropriate material in dielectric heating. Higher loss tangent leads to higher heating rate (Routray and Orsat 2014). Therefore, based on the 0.1 value, BC, GA, S and M with different DE are potential wall material to be used as low dielectric properties core material in microwave-encapsulation process. Even though the loss tangent of SC was below 0.1, SC is still possible to be used as wall material in microwave-encapsulation process but it must be used to encapsulate high dielectric properties core

Fig. 2 Relationship between dielectric constant and loss factor with bulk density at frequency of 2450 MHz

material as observed in the work of Abbasi and Rahimi (2008).

Relationship of dielectric constant and loss factor with bulk density

Figure 2 shows that the dielectric constant and loss factor values increased with the increase in bulk density of wall materials (Table 1). All wall material samples had a good linear relationship between dielectric constant and loss factor with density at 2450 MHz with large coefficients of determination; r^2 value of 0.9142 for dielectric constant and 0.9760 for loss factor. This linear relationship showed the important effect of bulk density on dielectric constant and loss factor of the wall materials that could be useful for estimating the density of wall material samples based on dielectric properties measurements. Indirectly, higher bulk density promotes higher dissipation of the wall material. This makes the wall material suitable to be used to encapsulate low dielectric core material using microwave-encapsulation drying process.

Conclusion

Dielectric properties of wall materials in the frequency range of 200 MHz to 10 GHz were measured using open-ended coaxial probe. The dielectric constant, loss factor and loss tangent values of these different wall materials were significantly influenced by composition, frequency and bulk density. From the result, it could be inferred that BC, S, GA and M with different DE exhibited effective encapsulation wall materials in microwave encapsulation-drying technique owing to their loss tangent values which were higher than 0.1 at general application frequency of 2.45 GHz. Thus, they were found to be suitable as wall material to encapsulate core material with low dielectric

Table 1 Relationship between dielectric constant and loss factor of different wall materials with density at 2450 MHz

Samples	Bulk density (g/ml)	Dielectric constant ϵ'	Loss factor ϵ''
SC	0.336	1.918	0.051
M(DE 13–17)	0.411	1.925	0.130
M(DE 4–7)	0.435	2.207	0.160
M(DE 16.5–19.5)	0.478	2.355	0.175
MI	0.486	2.388	0.220
CMC	0.621	2.477	0.291
S	0.639	2.900	0.303
GA	0.648	2.943	0.345
BC	0.740	3.206	0.428

Standard deviations ($\pm$ SD) mean values of bulk density, dielectric constant and loss factor was < 0.0001 , thus it could be neglected

properties in microwave encapsulation-drying process. On contrary, SC was found to be an ineffective wall material in microwave encapsulation-drying process since due to its loss tangent value of lower than 0.1. Nevertheless, SC has potential to be used as wall material to encapsulate high dielectric properties core material.

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