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A Simple Procedure to Determine Complex Permittivity of Moist Materials Using Standard Commercial Coaxial Sensor

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A simple procedure was developed to determine complex permittivity of moist materials for known percentage of moisture content at any frequency based using a standard commercial coaxial sensor. Polynomial fitting and Gaussian elimination method were applied to obtain a single equation of complex permittivity as a function of frequency and moisture content. The empirical equation was tested for new samples and was found to have mean error percentage of 5.14 % and 10.22 % for dielectric constant and loss factor, respectively, when compared to a commercial probe.

Keywords: Open ended coaxial line, permittivity, maize, empirical model

1. INTRODUCTION

AN OPEN ENDED coaxial line has been used by many researchers for measuring the complex permittivity of materials nondestructively [1]-[4]. In this method, the sample is placed against an open end of a coaxial line and its reflection coefficient is measured. A coaxial line having inner and outer radii aand b, respectively, filled with a lossless homogeneous dielectric having a relative permittivity is terminated in the plane z = 0 onto a flat metallic flange extending theoretically to infinity in the transverse direction [1]. The material terminating the aperture is assumed to be homogeneous, isotropic, linear, and nonmagnetic, of complex permittivity extending to infinity. The schematic diagram of an open ended coaxial sensor with a sample is shown in Figs.1a and 1b.

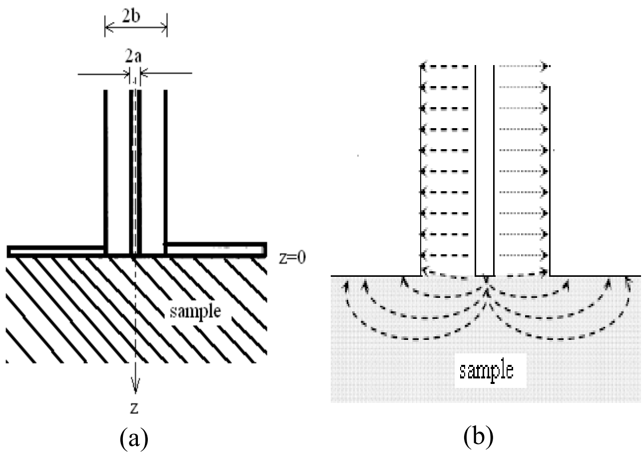

Fig.1. Open ended coaxial sensor [6] (a) Schematic diagram (b) Electric field distribution.

2. SUBJECT & METHODS

The most commonly used theoretical model for calculating the complex permittivity is the dielectric mixture model. The dielectric mixture is described in terms of the fractional volume and permittivity of each constituent. There are several mixture models that have been proposed [5]. There are Kraszewski (Kraszewski equation)

$$\sqrt{\varepsilon^*} = v_1\sqrt{\varepsilon_1} + v_2\sqrt{\varepsilon_2} + v_3\sqrt{\varepsilon_3} \quad (1)$$

Landau, Lifshitz and Looyenga, (Landau equation)

$$\sqrt[3]{\varepsilon^*} = v_1\sqrt[3]{\varepsilon_1} + v_2\sqrt[3]{\varepsilon_2} + v_3\sqrt[3]{\varepsilon_3} \quad (2)$$

Lichtenecker, (Lichtenecker equation)

$$\ln \varepsilon^* = v_1 \ln \varepsilon_1 + v_2 \ln \varepsilon_2 + v_3 \ln \varepsilon_3 \quad (3)$$

The notation used here applies to three component mixtures where ε^* represent the complex permittivity of the mixture, ε_1 is the permittivity of medium 1, ε_2 is the permittivity of medium 2 and ε_3 is the permittivity of medium 3. The v_1, v_2 and v_3 are the fractional volume of the respective components, where $v_1 + v_2 + v_3 = 1$ as the maize mixture consist of three main components. There are volume fractions of water, oil and fibre and this can be expressed as

$$v_{water} + v_{fibre} + v_{oil} = 1 \quad (4)$$

The permittivity of each component was measured using Agilent 85070B as listed in Table 1. The volume fraction of fibre is 0.17 [6].

The determination of the complex permittivity of maize begins with the establishment of an empirical model for moisture content (mc) in maize kernel. Typically, the diameter of a maize kernel is between 8 and 12 mm. The measurements were carried out at room temperature, 25°C for 250 kernels of maize with variation of moisture content from the youngest to the oldest fruit. It has been found that the moisture content for the youngest and the oldest kernel is 80% and 10%, respectively. The maize kernels were dried at 103 ± 1°C up to 72 hours using the air oven technique in accordance with the American Association of Cereal Chemist (AACC) techniques 44-15A [7].

Table 1. Dielectric constant and loss factor of water, oil and fibre at different frequencies

Freq (GHz)	ε_1 (water)	ε_2 (oil)	ε_3 (fibre)
1	78.2804 - 3.7957i	2.8977 - 0.1852i	3.9915 - 0.6372i
2	77.6916 - 7.5552i	2.8193 - 0.1784i	3.7943 - 0.5728i
3	76.7273 - 11.1869i	2.784 - 0.192i	3.5902 - 0.5785i
4	75.4209 - 14.6423i	2.7739 - 0.1969i	3.5247 - 0.6014i
5	73.8031 - 17.9119i	2.7489 - 0.24i	3.4024 - 0.5588i

The commercial sensor configuration and the calculation of permittivity were initially calculated using the procedure given in [8] for the frequency ranges 1 GHz to 5 GHz at room temperature. It has been found that the dielectric constant and loss factor changes with frequency in a linear form and the 4th order polynomial form, respectively, as shown in Figs.2 and 3. Relationship between the dielectric constant and loss factor with frequency can be described as

$$\varepsilon'(\mathrm{mc}, f) = \mathrm{A(mc)}f + \mathrm{B(mc)} \tag{5}$$

and

$$\varepsilon''(\mathrm{mc}, f) = \mathrm{C(mc)}\, f^4 + \mathrm{D(mc)}\, f^3 + \mathrm{E(mc)}\, f^2 + \mathrm{F(mc)}\, f + \mathrm{G(mc)} \tag{6}$$

where, *A, B, C, D, E, F,* and *G* are unknown variables that will be determined.

3. RESULTS AND DISCUSSION

The relationship between both dielectric constants, ε' and loss factor, ε'' of maize from 1 GHz to 5 GHz at various percentages of moisture content is shown in Figs.2a and 2b. It has been observed that the dielectric constant and loss factor are almost constant at low moisture content except for high moisture content. It is due to the small dispersion at low moisture content. The loss factor, ε'', decreases at low frequency, but increases again at 2 GHz. This behavior is influenced by ionic conductivity at lower frequencies, around 2 GHz, since the dielectric properties in agricultural products are primarily influenced by their ionic conductivity of fluids contained in their cellular structure [2]. The dielectric losses decrease with frequency according to $\sigma\omega^{-1}\varepsilon_0^{-1}$ [9] due to ionic conductivity. At low moisture content, it is difficult to measure moisture content since the moisture content in a maize kernel is non-uniform. That is why the increasing is not uniform at moisture content below 30%, whereby there is only a small difference between 17% and 22% moisture content, but the difference is much greater between 22% and 24% moisture content. This is probably due to the lack of accuracy of the Agilent coaxial probe sensor for reflection measurement of samples having low moisture, since the moisture content in a maize kernel is non-uniform. This is usually attributed to the effect of bound water detailed in [10]. Thus, this work only considers moisture content range between 32% and 80% moisture content.

Noisy behavior that occurs in 56% and 59% moisture content as shown in Fig.2 is probably caused by measurement errors during experimental work.

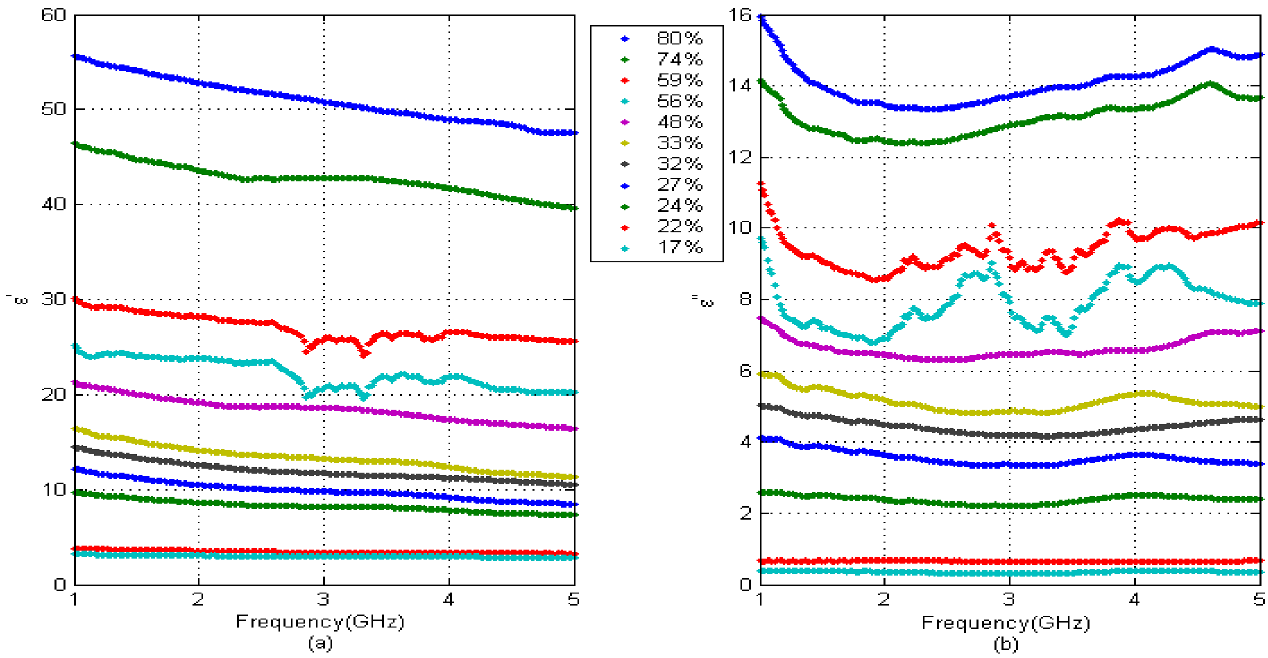

Fig.2. Relationship between (a) dielectric constant and (b) loss factor at various moisture contents for a maize kernel.

Table 2. Unknown variable as a function of moisture content for real and imaginary part of complex permittivity

ε^*	(*A, B, C, D, E, F* and *G*)
ε'	$A = 9.0913 \times 10^{-7} mc^4 - 1.9672 \times 10^{-4} mc^3 + 1.4922 \times 10^{-2} mc^2 - 0.4870mc + 4.943$
	$B = -1.4572 \times 10^{-6} mc^4 + 6.4072 \times 10^{-4} mc^3 - 6.4415 \times 10^{-2} mc^2 + 2.9131mc - 32.071$
ε''	$C = 1.3796 \times 10^{-7} mc^4 - 3.0113 \times 10^{-5} mc^3 + 2.2756 \times 10^{-3} mc^2 - 0.0668mc + 0.6214$
	$D = -2.2409 \times 10^{-6} mc^4 + 4.7203 \times 10^{-4} mc^3 - 3.4442 \times 10^{-2} mc^2 + 0.9797mc - 8.9526$
	$E = 1.1238 \times 10^{-5} mc^4 - 2.3274 \times 10^{-3} mc^3 + 0.1668mc^2 - 4.6510mc + 41.954$
	$F = -1.8791 \times 10^{-5} mc^4 + 3.8955 \times 10^{-3} mc^3 - 0.2791mc^2 + 7.7051mc - 68.850$
	$G = 2.0664 \times 10^{-6} mc^4 - 5.3044 \times 10^{-4} mc^3 + 4.4260 \times 10^{-2} mc^2 - 0.9674mc + 6.0431$

The unknown variables *A, B, C, D, E, F,* and *G* were determined using the Gaussian Elimination method. The unknown variables as a function of moisture content are tabulated in Table 2. The empirical fitting for the determination of complex permittivity was established as described in Table 2. The empirical model was used to estimate the complex permittivity as a function of moisture content and was compared with measured and calculated permittivity that were found using selected mixture models such as Kraszewski, Landau and Lichtenecker.

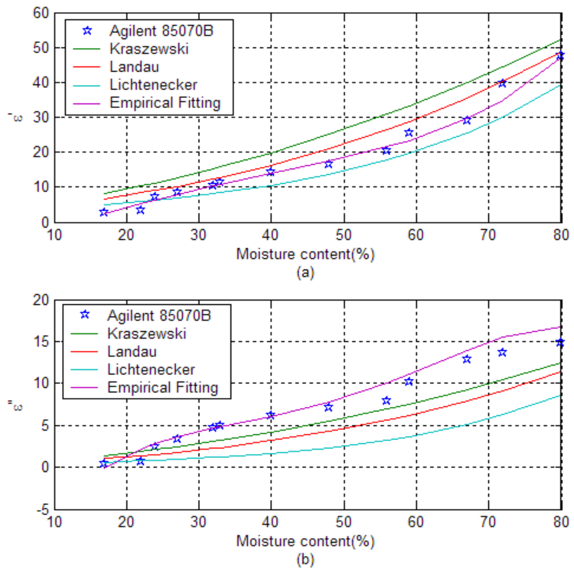

Fig. 3. Relationship between (a) dielectric constant and (b) loss factor with moisture content for experimental results, mixture models (Kraszewski, Landau and Lichtenecker) and empirical fitting at 5 GHz.

The result for the empirical model shows a good agreement with experimental results compared with the mixture model for both dielectric constant and loss factor. It is clearly shown in Fig. 3, whereby the empirical fitting is the closest to the measured data. The accuracy of the empirical model can be described using relative error. The relative error for the empirical model and mixture model is based on the measurement data as described in (7).

$$relative\ error = \left| \frac{Measured - X}{Measured} \right| \tag{7}$$

where the measured data was obtained from Agilent 85070B and X is either Kraszewski, Landau, Lichtenecker or empirical fitting. The comparisons of the relative error for empirical model, Kraszewski mixture model (1), Landau mixture model (2) and Lichtenecker mixture model (3) are shown in Tables 3 and 4 for the dielectric constant and loss factor, respectively.

Table 3. Relative error for calculated dielectric constant

	Dielectric constant			
MC(%)	Empirical	Eq. 1	Eq. 2	Eq. 3
32	0.0099	0.5361	0.2748	0.2545
33	0.0383	0.4851	0.2445	0.2815
48	0.0684	0.6236	0.3773	0.2183
56	0.0618	0.6272	0.4108	0.2010
59	0.0880	0.4216	0.2720	0.2724
67	0.0164	0.4930	0.3506	0.2126
72	0.1189	0.2898	0.2314	0.2868
80	0.0095	0.2787	0.2397	0.2522
Mean	0.0514	0.4694	0.3001	0.2474

Table 4. Relative error for calculated loss factor

	Loss factor			
MC(%)	Empirical	Eq. 1	Eq. 2	Eq. 3
32	0.0035	0.3432	0.5164	0.7477
33	0.0360	0.3615	0.5284	0.7544
48	0.0798	0.2331	0.3992	0.6745
56	0.2743	0.1191	0.2834	0.5884
59	0.0875	0.2589	0.3882	0.6390
67	0.0769	0.2832	0.3846	0.6049
72	0.1310	0.2390	0.3301	0.5431
80	0.1288	0.1671	0.2373	0.4208
Mean	0.1022	0.2506	0.3834	0.6216

Tables 3 and 4 show clearly that the empirical model give the smallest relative error for the dielectric constant and loss factor compared to the mixture model. The relative error for loss factor is higher compared to the dielectric constant due to the range between loss factor of water and dry maize, which is smaller compared to the dielectric constant. It means that the sensitivity for determination of the dielectric constant of maize is higher compared to loss factor.

4. CONCLUSION

The empirical equation of complex permittivity as described in Table 2 is a combination between real and imaginary part. This equation can be used to predict the dielectric constant and loss factor of maize. This equation is best for the prediction of moisture content between 32% and 80% with percentage mean error 5.14% and 10.22% for the dielectric constant and loss factor, respectively. This model is applicable only in the frequency range 1 GHz to 5 GHz.

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