



Dielectric properties of the small granular agricultural products in the microwave frequency band

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ABSTRACT

Microwave drying and non-destructive sensing of agricultural products based on dielectric properties is an important field of modern agricultural research. The present study was carried out to improve the traditional coaxial transmission line technology and get some basic dielectric properties of agricultural products from Yunnan province of China during year 2018-19. The effective dielectric properties of vegetable seeds, coarse cereals, and grass seeds from China are measured by a non-calibrated coaxial transmission reflection method at 2~6 GHz in this work. The dielectric properties of the small granular agricultural products are obtained by relevant theoretical formulas, and variations in the dielectric properties of granular agricultural products as a function of the microwave frequency and moisture content were analysed. The results show that the dielectric properties of small granular agricultural products at room temperature are related to the microwave frequency and moisture content with a certain degree of regularity. At 2.45 GHz and for a moisture content between 2%~25%, the dielectric constants and dielectric loss factors for different kinds of small granular agricultural products ranged from 3.5~9 and 0.1~2, respectively. The mathematical relationships between the dielectric properties and moisture contents of granular agricultural products were obtained by fitting the experimental data to the microwave frequency (2.45 GHz). This work provides a reference method for measurement of dielectric properties of granular agricultural products, and the theoretical basis for the microwave assisted processing of agricultural products.

Key words: Dielectric property, Measurement techniques, Microwave frequency, Small granular agricultural products

Dielectric properties (ϵ) refer to the response characteristics of a bound charge in the molecules in a medium to an external electric field and is mainly represented by the dielectric constant (ϵ') and the dielectric loss factor (ϵ''): $\epsilon = \epsilon' - j\epsilon''$. The dielectric properties are used to study microwave-assisted applications in non-magnetic agricultural medium (Nelson *et al.* 2016). In past decades and according to the needs of microwave processing, storage, preservation, sterilization, grading and testing of agricultural products, many scholars have studied the dielectric properties of agricultural products using different technological methods. Nelson studied the dielectric properties of cereals in 1965 and used this work to design an electric moisture meter, and his researches show that the dielectric properties of agricultural products decreased as the frequency increased, whereas the dielectric loss factor may increase or decrease. Subsequently, he carried out lots of research works on the measurement technology of dielectric properties of agricultural products and the influencing factors

of dielectric properties (temperature, frequency, density, moisture, etc.), the main research objects were rice, seeds, corn, wheat, vegetables and fruits (Nelson 2005, Nelson *et al.* 2012), and he summarized the research works in 2015 (Nelson 2015). In addition, Chee analysed the dielectric constant and its relationship with the moisture constant of freeze-dried potato chips at a frequency of 2.45 GHz using the electromagnetic spectral technique (Chee *et al.* 2014). Sipahioglu measured the dielectric properties of bananas at frequency 2.45 GHz and within a temperature range from 5-130°C to determine that the dielectric loss factors of vegetables and fruits first decreased and then increased with the temperature (Sipahioglu *et al.* 2010). Shrestha analysed the relationships of the dielectric properties of different vegetables and meats with temperature, frequency and density using a cylindrical resonator (Sheathe and Baik 2013). The scholars pointed out that agricultural products are basically hygroscopic electric media and their polarization was enhanced after wetting, resulting in increasing dielectric constants. The dielectric property measurements of agricultural products are now becoming very important and have promising prospects for future applications. Previous research has facilitated the microwave thermal processing applications of agricultural products, as well as associated

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product development. Nevertheless, there are many types of agricultural products in nature. Currently, research into the measurement of dielectric properties of agricultural products mainly focused on fresh vegetables, fruits and major cereals (e.g. wheat and rice), which have high dielectric constants and involved few types and quantities of agricultural products (Guo *et al.* 2014).

In earlier studies, parallel plate technology, coaxial probe technology, transmission line technology, cavity resonator technology, and free space technology are mainly used to measure the dielectric properties of materials. Different technical methods have corresponding advantages and disadvantages (Nelson 2015). For example, the parallel plate technique is suitable for measuring the dielectric properties of materials with parallel interface in low frequency band. The cavity resonator technology can only measure the dielectric properties at single frequency. The coaxial probe technique is suitable for the measurement of dielectric properties of liquid or semisolid materials, but the accuracy of this method is limited for materials with small dielectric constant and loss factor. The precision of transmission line technique is higher than the coaxial probe technique, but it is more troublesome for sample preparation, and the characteristics of free space technology are non-contact and nondestructive, but the calibration of network analyzer is very troublesome.

In this study, we improved the traditional coaxial transmission line technology according to the structure shape and physical characteristics of the small granular agricultural products, and measured the dielectric properties of the rapeseed grains, the grain particles and the grass seed particles under the high frequency band (microwave band) by using the non-calibrated coaxial transmission reflection method. The correlations between the dielectric constant and dissipation factor for different agricultural products vary with microwave frequency and moisture content. The relationship between the dielectric properties and moisture content of agricultural products at 2.45 GHz was obtained by fitting. The macroscopic laws for the dielectric properties of granular agricultural products at microwave frequencies were analysed.

MATERIALS AND METHODS

Materials and devices: All agricultural products were purchased from seed shops in Yunnan, China (latitude: 24.87, longitude: 102.85, altitude: 1951), in 2018 and purified before storing in polyethylene plastic bags. All products were restored to room temperature prior to measurement. Three types of agricultural products were selected: rapeseeds (white-leaf amaranth, mustard, bright red amaranth, sweet rapeseed, cabbage seed, bittercress and rapeseed), cereal seeds (black sesame, maize pulp, black rice and millet) and grass seeds (bluegrass, *Trifolium repens*, corn poppy, *Agrostis flaccid*, Bermuda grass and *Chrysanthemum nigra*). Experimental instruments and equipment included a ZNB20 vector network analyzer (Rohde & Schwarz Ltd, Germany), an 85051B 7 mm/APC-7 coaxial airline (Agilent Technology,

Malaysia) and a moisture content detector (China, weighting accuracy=0.005 g).

Moisture content measurements: Three parallel experiments on the same sample were carried out using the moisture content detector based on the drying principle. The mass difference was less than 5 mg and the arithmetic mean value was used as the test value. To acquire samples with relatively high moisture content, the testing substances were immersed in water for 1 h to absorb water. Next, they were dried naturally in air over 5 h to assure complete evaporation of the surface water. Moisture content was measured and recorded. To acquire samples with low moisture content, they were dried appropriately according to the experimental demands. The moisture content was measured and recorded after returning to room temperature. The samples were measured one by one.

Measuring system improve: Two Teflon sheets with inner and outer diameters conforming to a coaxial transmission line were used as the separator to ensure that the microwave penetrated the agricultural products in the high-frequency band. The samples were placed in the region between these two Teflon sheets in the coaxial transmission line. 85051B coaxial transmission line clamps were connected to two ports of the ZNB20 vector network analyzer by an APC-7~3 mm adapter and coaxial cable. The ZNB20 network analyzer was preheated and the S parameter measurement system (no calibration) of the network analyzer was started 1 h later. In the measurement, the frequency range was set between 2~6 GHz according to the operation specifications, and 201 frequency points were selected at equal intervals. Each measurement was scanned repeatedly 20 times and the arithmetic mean value was used.

Experimental measurement: The tested samples were placed at room temperature (24±1°C) or approximately 5 h to ensure recovery to room temperature. The measurement was divided into two steps. (1) The Teflon sheets were placed in the coaxial airline. The S parameter of the coaxial line was filled with air and the Teflon was measured three times after stabilization and then stored. (2) The testing particles were placed between the two Teflon sheets. The S parameter of the mixture composed of air, Teflon and the test particles was measured three times and stored after stabilization. After finishing the measurement, the volumes of the particle materials were measured and recorded via the drainage method.

Calculation of effective dielectric properties of the mixture: According to the measurement principle of a non-calibration coaxial transmission line (Zhao 2011), the measured value of the S parameter and the mathematical equation of effective dielectric properties of the testing mixture were determined from the electromagnetic field theory and T-matrix conversion related theory. The equation was calculated via Newton's iterative numerical calculation method. The relevant program was compiled using MATLAB to determine the numerical value of the complex relative dielectric constant describing the dielectric properties of the testing mixture.

Calculation of the volume fraction: The volume of the tested granular materials, V_1 , was tested by the drainage method. Based on the distance d between the two Teflon sheets in the coaxial airline, the volume of the coaxial airline section between the two thin sheets was calculated to be $V_2 = \pi (b^2 - a^2)d$ where b and a are the outer and inner diameters of the coaxial line. On this basis, the volume fraction of the granular materials in the air/granular material mixture was calculated by $f_v = V_1/V_2$.

Calculation of the dielectric properties of granular materials: The effective dielectric properties of the mixture were obtained by experimental measurements, and the dielectric properties of the granular agriculture were calculated by the Brichak formula.

Data processing and analysis: Data processing and analysis were accomplished using MATLAB R2012a (Math Works, Massachusetts, America) and Origin 8.5 (Atos Origin, Amsterdam, Netherlands).

RESULTS AND DISCUSSION

Verification of Measurement Scheme: In order to verify the reasonableness and accuracy of the Brichak formula, a dry snow-air mixture ($\epsilon_i = 3.15 - j0.0001$, $\epsilon_e = 1$), which has a similar dielectric constant as the agricultural product-air mixture was chosen as the research object. A comparison between the numerical results calculated using different theoretical formulas and the measured value in a previous study (Shivola 1989). The numerical result calculated by the Brichak formula agrees the best with the measured value. In addition, the Nelson's research show that the calculated results from wheat grain and powder determined

using the Brichak formula are in good agreement with the experimental results (Nelson 2005). Hence, the Brichak formula is used to convert the effective dielectric properties of the air-solid mixtures into the dielectric properties of the granular agricultural products. In order to verify the correctness of the measurement scheme, the scattering parameters of the paraffin particle samples were measured (the average after repeated measurement three times), the dielectric constant of paraffin is 2.238, and dielectric loss tangent value is 0.0031. The calculation coincides with the experimental value (Han *et al.* 2013). The results show that the non-calibration coaxial transmission reflection method can be used to measure the dielectric properties of the agricultural products in the microwave frequency band. This technological method is also applicable to dielectric property measurement and the analysis of other small granular particles.

Relationship between the dielectric properties and the microwave frequency: The dielectric properties of 17 small granular agricultural products for single moisture content are measured. Black sesame, maize pulp, black rice and millet were chosen as the research objects to investigate coarse cereals. The volume fractions of these cereal particles in the gas-solid mixture were 0.598, 0.513, 0.598 and 0.598, respectively. White-leaf amaranth, mustard, bright red amaranth, sweet rapeseed, cabbage seed, bittercress and rapeseed were chosen as the research objects to investigate rapeseed. Their volume fractions were 0.684, 0.598, 0.684, 0.556, 0.684, 0.513 and 0.598, respectively. Bluegrass, *Trifolium repens*, corn poppy, *Agrostis flaccid*, Bermuda grass and *Chrysanthemum nigra* were chosen as the

Table 1 Measurement data of dielectric properties of different kinds of Granular Agricultural Products in the microwave frequency

Agricultural product	Moisture (%)	Volume fraction	Microwave frequencies									
			2.0 GHz		3.0 GHz		4.0 GHz		5.0 GHz		6.0 GHz	
			ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''
Black sesame	8.99	0.598	3.474	0.228	3.247	0.208	3.178	0.210	3.223	0.201	3.177	0.167
Millet	12.5	0.513	4.506	0.632	4.172	0.550	4.084	0.541	4.033	0.512	4.012	0.456
Maize pulp	12.05	0.598	5.602	0.981	5.167	0.973	5.049	0.925	4.903	0.788	4.759	0.745
Black rice	14.17	0.598	5.090	0.851	4.760	0.775	4.699	0.783	4.653	0.677	4.493	0.609
White amaranth	12.36	0.684	4.088	0.122	3.986	0.118	3.908	0.116	3.824	0.111	3.779	0.109
Mustard	8.19	0.598	2.495	0.539	2.468	0.524	2.459	0.505	2.442	0.483	2.428	0.449
Bittercress	10.64	0.684	4.584	0.130	4.465	0.124	4.386	0.123	4.309	0.120	4.250	0.121
Red amaranth	9.60	0.556	5.601	0.553	5.250	0.524	5.232	0.503	5.273	0.480	5.117	0.465
Cabbage seed	13.29	0.684	2.376	0.697	2.356	0.603	2.348	0.604	2.329	0.530	2.316	0.455
Sweet rapeseed	12.10	0.513	2.982	0.341	2.993	0.310	3.017	0.293	2.947	0.267	2.926	0.300
Rapeseed	16.40	0.598	4.370	0.651	4.098	0.606	3.962	0.586	3.942	0.530	3.834	0.494
Bluegrass	14.22	0.598	4.957	0.902	4.460	0.769	4.268	0.769	4.314	0.687	4.288	0.690
Corn poppy	9.82	0.684	3.861	0.360	3.802	0.349	3.730	0.349	3.658	0.304	3.594	0.257
Acrostics flaccid	12.01	0.513	3.398	0.423	3.324	0.410	3.296	0.410	3.240	0.403	3.174	0.431
Chrysanthemum	8.84	0.598	3.366	0.287	3.283	0.278	3.232	0.278	3.164	0.249	3.129	0.223
Bermudagrass	11.50	0.513	4.596	0.524	4.277	0.438	4.224	0.438	4.285	0.405	4.172	0.387
<i>Trifolium repens</i>	11.84	0.427	3.652	0.312	3.611	0.300	3.564	0.300	3.511	0.269	3.459	0.225

research objects to investigate grass seeds. Their volume fractions were 0.598, 0.684, 0.513, 0.598, 0.513 and 0.427, respectively.

The experimental values of dielectric constant and dielectric loss factor are shown in Table 1, respectively, and show that the dielectric properties of small granular agricultural products are mutually related to the microwave frequency. For the same moisture (oil) content, the dielectric constant of small granular materials decreased as frequency increased at room temperature conditions, whereas the dielectric loss factor may increase or decrease. The dielectric constants and dielectric loss factors of agricultural products with high moisture (oil) content changed greatly with frequency. This might be related to the microwave penetration ability and the shape and size of particles. This varying law agreed with the dielectric parameter change laws for winter wheat measured by the resonant cavity method (Nelson and Trabelsi 2016). The agricultural product with mixed multiple particle shapes (e.g. maize pulp) had a higher dielectric constant. This may be due to the substance being derived from the late-milling of cereals, resulting in significantly different particle shapes. The dielectric constants and dielectric loss factors for granular samples (e.g. black rice) with a high water (oil) content changed dramatically as a function of frequency. Small rapeseed with a high density (e.g. bright red amaranth, white-leaf amaranth, bluegrass and Bermuda grass) exhibited higher dielectric constants, which may be attributed to their high conductivity and low air clearance rate. Moreover, the dielectric constant and dielectric loss factor of bright red amaranth was the highest, despite its moisture content being only 9.6%. However, the dielectric constant and dissipation factor of white-leaf amaranth was

the lowest, despite the moisture content reaching 13.29%.

Relationships of dielectric properties with moisture content: Millet (coarse cereal), bright red amaranth (rapeseed) and bermuda grass (grass seed) were chosen to study the relationship between the dielectric properties and moisture (oil) content of the different types of granular agricultural products. Samples with different moisture (oil) contents were prepared by the method according to *Moisture content measurements*. The moisture contents and the measurement results of dielectric properties are shown in Table 2, and demonstrate that the agricultural products with higher moisture (oil) content had higher dielectric constants and dielectric loss factors. For the same microwave frequency, the dielectric constant and dielectric loss factor of the small granular materials increase with the moisture (oil) content. Moreover, the dielectric properties changed more dramatically with moisture (oil). When the moisture (oil) content was higher than 20%, the stability of the dielectric properties of samples decreased at high frequencies due to water molecular interactions in the substances. For example, when the moisture (oil) content of the millet was 23.58%, the dielectric loss factor began to jump after 4 GHz, and the moisture (oil) content of the Bermuda grass was 21.11%, the dielectric loss factor jumped increased near 5GHz.

Relationship between the dielectric properties and moisture content at civil microwave frequency: A civil microwave frequency of 2.45 GHz was applied to guide microwave-assisted applications of agricultural products. The variations in the dielectric properties of different granular agricultural product types as functions of the moisture content are shown in Fig 1. At the civil microwave frequency (2.45 GHz), the dielectric properties of different granular agricultural products changed differently with

Table 2 Measurement data of dielectric properties of agricultural particles with different moisture content in the microwave frequency (GHz)

Atricultural products	Moisture (%)	2.0 GHz		3.0 GHz		4.0 GHz		5.0 GHz		6.0 GHz	
		ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''	ϵ'	ϵ''
Millet	2.00	3.547	0.279	3.322	0.214	3.258	0.193	3.309	0.162	3.274	0.129
	5.50	3.706	0.371	3.461	0.298	3.407	0.279	3.47	0.254	3.439	0.243
	12.50	4.506	0.632	4.172	0.55	4.084	0.541	4.133	0.512	4.012	0.456
	18.20	5.123	0.834	4.698	0.745	4.587	0.753	4.63	0.736	4.477	0.714
	23.58	5.602	1.003	5.167	0.913	5.049	0.921	4.903	0.868	4.759	0.658
Bright red amaranth	1.90	4.139	0.297	3.921	0.23	3.902	0.215	3.967	0.185	3.898	0.171
	5.90	4.79	0.697	4.525	0.603	4.508	0.604	4.568	0.53	4.447	0.455
	9.60	5.601	1.579	5.25	1.508	5.232	1.73	5.273	1.623	5.117	1.502
	15.10	6.262	0.439	5.826	0.361	5.795	0.348	5.814	0.3	5.532	0.294
	21.50	8.136	1.011	7.562	0.9	7.647	0.926	7.4	0.792	7.234	0.535
Bermuda grass	1.80	3.77	0.34	3.539	0.268	3.514	0.253	3.562	0.223	3.524	0.225
	5.90	4.08	0.524	3.818	0.438	3.783	0.427	3.855	0.405	3.809	0.387
	11.50	4.596	1.4	4.277	1.301	4.224	1.422	4.285	1.395	4.172	0.392
	17.11	5.903	0.286	5.422	0.22	5.296	0.205	5.311	0.172	5.109	0.163
	21.11	7.196	1.037	6.6	0.924	6.54	0.918	6.593	0.847	6.254	0.658

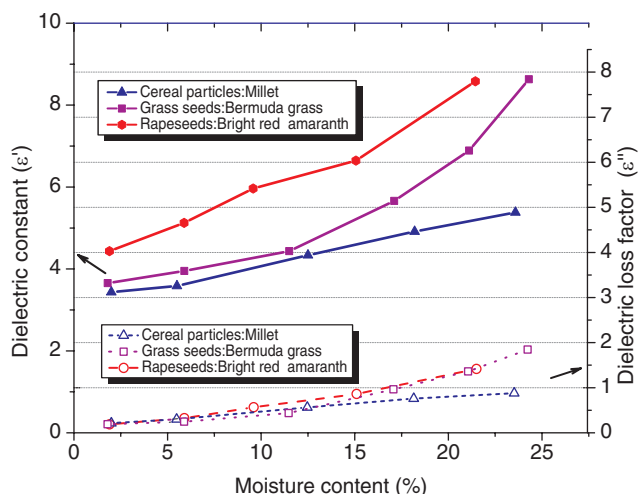


Fig 1 Relationships between the dielectric properties (dielectric constant and dielectric loss factor) and moisture content of the small granular agricultural products at 2.45GHz.

moisture content. Generally, the dielectric constants of the agricultural products were between 3.5~9 and the dielectric loss factors were between 0.1~2 for moisture contents range from 2% to 25%. This macroscopic phenomenon can be used as a reference for microwave-assisted applications of granular agricultural products.

To determine the predictive equations for the dielectric properties of granular agricultural products at different moisture contents, the dielectric constants, dielectric loss factors and moisture (oil) contents of the granular substances were set to be ϵ' , ϵ'' and M (%). The mathematical relationship between the dielectric properties and moisture contents of the three granular agricultural products at 2.45 GHz were determined by fitting the curves in Fig 1 (shown in Table 3 where R^2 is R-square). Meanwhile, the relationships between the mean dielectric properties and the moisture contents of the three substances were fitted to determine a general equation describes all granular agricultural products. Although this general equation can predict varying trends in the dielectric properties for different granular products as functions of moisture content, they still have limited accuracy for high moisture contents ($M > 20\%$). Great deviations between the predicted and measured values in the dielectric loss factors for some granular substances (e.g. millet) were observed for high moisture contents (the deviation amplitude reached 25% when the moisture content greater than 20%). Based on the analysis, we conclude the following: due to the different structures and compositions associated with the granular agricultural products, it is difficult to establish a high-accuracy general equation for the dielectric properties of different types of granular agricultural products. This general equation is only applicable to the macroscopic prediction of the dielectric properties. However, a good mathematical formula was identified to describe the relationship between the dielectric properties and moisture contents in the same agricultural product. In future work, it

Table 3 Mathematical relationship between the dielectric properties and moisture content for different types of small granular substances

Matter	Dielectric constant	Dielectric loss factor
Millet	$\epsilon' = 3.1672 + 0.0941M$ ($R^2 = 0.997$)	$\epsilon'' = 0.1461 + 0.032M$ ($R^2 = 0.991$)
Red amaranth	$\epsilon' = 3.5785 + 0.1895M$ ($R^2 = 0.992$)	$\epsilon'' = 0.007 + 0.069M$ ($R^2 = 0.973$)
Bermuda grass	$\epsilon' = 3.8984 + 1.878M$ $+ 0.01135M$ ($R^2 = 0.989$)	$\epsilon'' = 0.2172 + 0.0185M$ $+ 0.0035M$ ($R^2 = 0.997$)
Common matte	$\epsilon' = 3.1484 + 0.1628M$	$\epsilon'' = -0.0047 + 0.0581M$

is valuable to continue to study the dielectric properties of small granular agricultural products under the conditions of temperature change and density change.

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