Dielectric properties of whole, chopped and powdered grain at various bulk densities

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[1]Department of Agricultural and Biosystems Engineering, Macdonald Campus of McGill University, Ste-Anne-de-Bellevue, QC, Canada H9X 3V9; and [2]Poly-grames, Ecole Polytechnique de Montréal, 3333 Queen Mary, 2nd stage, Montréal, QC, Canada H3V 1A2. *Received 26 September 1997; accepted 11 June 1998.*

Venkatesh, M.S., St-Denis, E., Raghavan, G.S.V., Alvo, P. and Akyel, C. 1998. **Dielectric properties of whole, chopped and powdered grain at various bulk densities**. Can. Agric. Eng. **40**:191-200. The dielectric properties of whole, chopped, and powdered corn and wheat kernels were determined at 915 MHz and 24°C by the cavity perturbation technique. Existing cubic and quadratic relations were respectively found to describe adequately the functional dependence of dielectric constant and loss on grain sample bulk density. The hypothesis that the dielectric response of particulates with non-homogeneous layers could change as a result of size reduction was investigated. The data suggest, but do not confirm, this possibility. A more detailed study including proximate analyses and moisture determinations of the fractions would be required.

Il est reconnu que les propriétés diélectriques des matériaux soumis aux micro-ondes varient selon le taux d'humidité, la température, la composition, et la densité des matériaux de même que selon la fréquence du champ électromagnétique. Les effets de la densité apparente et de la granulométrie sur les propriétés diélectriques des grains ont été étudiés. Les relations linéaires existant entre le carré des propriétés diélectriques et la densité que l'on retrouve dans la littérature, ont été validées avec la méthode de perturbation des cavités, pour des grains concassés et en poudre. L'effect de la granulométrie sur les propriétés diélectriques des grains concassés est une relation quadratique. Il n'existe cependant pas de relation "pure et exacte" entre les propriétés diélectriques et la granulométrie, comme on pouvait s'y attendre de façon théorique, mais les résultats peuvent tout de même être utilisés afin de valider les modèles cubique et quadratique reliés à la densité.

INTRODUCTION

The dielectric properties of a material explain the nature and degree of interaction between a material and an applied electromagnetic field and can be used to predict processing parameters such as the dielectric heating rate. The dielectric properties depend mainly on the moisture content, temperature, and chemical composition of the material and vary according to the frequency of the applied electromagnetic field. However, in predicting heating rates in a processing application, factors such as bulk density and shape must also be taken into account. Relationships between dielectric properties and air-particle mixtures were previously developed by Nelson (1983a, 1983b; 1984b, 1991) and applied to grains.

Grains are an example of a material that may be thermally processed at different bulk densities for different applications. For example, one may dry whole kernels for long-term storage, or one may need to thermally treat crushed grain or finer forms such as flour. Furthermore, for a given particle size of material, geometric factors such as bed height and width may also influence the bulk density of the bed by altering the static pressure distribution. One may also choose to pack or loosen the material prior to conveying it through the processing chamber to manipulate heating/aeration parameters. Thus, it is important to know the dielectric properties of such materials at different bulk densities.

One aspect that has received little attention to date is that of a possible dependence of dielectric properties on particle size. Although it is generally considered that there should be no such dependence, we suggest that when particles with several layers of different materials are fractured, the bulk dielectric response could change due to the change in relative depth of components with different basic dielectric properties. Underlying this suggestion is the idea that the dielectric response of a single grain kernel is a function of the cross-sectional moisture and material gradients, since these gradients affect the power density attenuation.

The main objective of this study was therefore to determine the relationships between the dielectric properties of corn and wheat, ground to various extents and compressed to various bulk densities. A preliminary study of the possible effects of particle sizes on dielectric properties was also conducted with the same materials.

ASPECTS OF MICROWAVE INTERACTIONS WITH BIOLOGICAL MATERIAL

Permittivity of a material is an important parameter to consider in microwave drying because of its correlation with process variables such as material moisture content, bulk density, and temperature as well as the frequency of the alternating electromagnetic field.

The permittivity ε^* is usually defined as (Ryynänen 1995):

$$\varepsilon^* = \varepsilon_0(\varepsilon' - j\varepsilon'') \quad (1)$$

where:

ε' = dielectric constant,

ε'' = dielectric loss factor, and

ε_0 = free space permittivity (8.854×10^{-12} F/m).

The dielectric constant ε' is associated with the ability of a dielectric material to store or couple electromagnetic energy, whereas the dielectric loss factor ϵ" represents its ability to dissipate energy.

The most important factors affecting the dielectric properties of grain, as stated by Nelson (1982), are the moisture content and temperature as well as the frequency of the alternating electromagnetic field. Density has also been identified as a major source of variation of ϵ' and ϵ" (Kent 1977; Nelson, 1983a, 1983b, 1984a, 1984b; Kent and Kress-Rogers 1986; Nelson and You 1989; Trabelsi et al. 1997). The density dependence of the dielectric properties of particulate materials must be accounted for in elaborating functions determining grain moisture content (Powell et al. 1988; Meyer and Schilz 1980). This relation could also be used in the control of continuous on-line thermal processing of grain. In the case of moisture determination by microwave methods, the frequency employed should be above 5 GHz to avoid the influence of ionic conductivity and bound water relaxation (Kraszewski 1988). Dielectric properties vs density relationship studies have been concentrated at high frequencies. However, the size of microwave components is usually proportional to the wavelength and therefore inversely proportional to frequency. If microwave power is to be applied to grain for drying purposes, better penetration can be achieved at lower microwave frequencies.

The allowed microwave frequencies commonly used for industrial, medical, and scientific (ISM) applications in North America are 915 MHz and 2450 MHz (Metaxas 1996). At these frequencies, the penetration depth in the material will allow a reasonable processing rate/cost ratio. Therefore, it is interesting to investigate the applicability of the existing models (Nelson 1983a, 1983b) at these microwave frequencies.

At frequencies > 200 MHz and into the microwave region, transmission-line and resonant cavity techniques have been useful (Nelson 1991). Most of the data and models found in the literature were obtained with methods in which the sample material filled a portion of the waveguide, such as the short-circuited line technique (Nelson and You 1989) or the microwave bridge technique for measuring microwave attenuation and phase shift (Kent and Kress-Rogers 1986). Resonant cavity perturbation is a technique which uses two circuit parameters; the shift in resonant frequency, Δf, and the *Q* factor of the cavity, to quantify the dielectric properties.

When a small sample of dielectric material is introduced into a resonant cavity, the frequency of resonance and the quality factor *Q* of the cavity change slightly. These effects are commonly used in the measurement of the dielectric properties of the sample (Altschuler 1963; Waldron 1967). The shift in resonant frequency is considered to be mainly correlated with the dielectric constant, while the change in the *Q* factor is associated with the dielectric loss. The *Q* factor consists of quantification of the sharpness of the peak of the resonance curve. Thus, when an object is introduced into the cavity, the resonant frequency will decrease and the *Q* factor will be lowered, causing a broader, flatter resonance curve (Kraszewski and Nelson 1994). An advantage of the cavity perturbation technique is the simplicity of the measurement setup. It does not require complicated calibrations and tuning since a network analyzer can accomplish most of the sensing functions.

The cavity (TM_{010}) perturbation technique has been used successfully to measure the dielectric properties of granular material (Li et al. 1981). In this study, the equations relating ϵ' and ϵ" to Δf and ΔT (perturbation equations) are in the form:

$$\Delta f = 2(\varepsilon' - 1) K f_0 \left(\frac{v_s}{v_0} \right) \tag{2}$$

$$\Delta T = 4\varepsilon'' K^2 Q_0 \left(\frac{v_s}{v_0} \right) \tag{3}$$

where:

- v_o = volume of empty cavity,
- v_s = volume of the sample,
- Δf, ΔT = shift in resonant frequency and change in cavity transmission factor, related to cavity Q,
- f_o = resonant frequency of the empty cavity,
- Q_o = Q factor of the empty cavity, and
- K = factor dependent upon the shape, orientation, and permittivity of the sample (Kraszewski and Nelson 1994).

MATHEMATICAL RELATIONSHIPS

The bulk density (ρ) of grain is the second most important factor, after moisture content, affecting the dielectric properties of grain at a given frequency and temperature (Nelson 1982). It has been shown that certain functions of the dielectric properties of particulate materials vary approximately linearly with the bulk density of the air-particle mixtures (Nelson 1983a, 1983b, 1984a, 1991). These relationships are in the form:

$$(\varepsilon')^{1/2} = m_1 \rho + 1 \tag{4}$$

$$(\varepsilon'' + e)^{1/2} = m_2 \rho + (e)^{1/2} \tag{5}$$

$$(\varepsilon')^{1/3} = m_3 \rho + 1 \tag{6}$$

where:

- m_1, m_2, m_3 = constants for the slope of the straight lines,
- ρ = density of air-particle mixture,
- e = constant dependent upon the material, and
- ϵ', ϵ" = 1 and 0, respectively for air alone (ρ = 0).

Equations 4 and 5 are consistent with the quadratic relationship between dielectric properties and density reported by Kent (1977) for data on fishmeal.

$$\varepsilon' = a\rho^2 + b\rho + 1 \tag{7}$$

$$\varepsilon'' = c\rho^2 + d\rho \tag{8}$$

where a, b, c, d = constants.

The similarity between Eqs. 4 and 7 and Eqs. 5 and 8 is evident if one considers that $a = m_1^2$, $b = 2m_1$, $c = m_2^2$, and $d = 2\,m_2\,(e)^{1/2}$. Thus the measurement of the permittivity of a particulate material at a given density, along with the (ρ=0, ϵ'=1) intercept, provides information on the permittivity at all densities, including the solid material, if its density is known. Comparison of Eqs. 5 and 8 leads to the condition:

$$e = \frac{d^2}{4c} \tag{9}$$

Equation 6 was reported to give a more reliable determination of the dielectric constant (Nelson 1983a, 1983b, 1984a, 1991; Nelson and You 1989). It is also consistent with a proven mixture formula which specifies the additivity of the cube roots of the dielectric constants of the constituents of a mixture when taken in proportion to their volume fractions (Nelson 1984a).

Equations 4 to 8 all conform to the theory that when $\rho = 0$, the values of the dielectric properties are those of free space (or air); $\epsilon' = 1$ and $\epsilon'' = 0$. The advantage of Eqs. 4 to 6 is that they can be easily extrapolated to values of density exceeding the range of measurements. This can be quite helpful in the case of grains such as corn and wheat.

In the present study, the linear relationships were used as a means of eliminating the density effect. By having the appropriate linear relationships, it is possible to calculate the dielectric properties at a common density so that the desired effect, particle size, is the only variable parameter.

MATERIALS AND METHODS

Samples of clean shelled yellow-dent field corn, *Zea mays L.*, and hard red winter wheat, *Triticum aestivum L.*, were used for the experiment. The corn moisture content (m.c.) was 13.6 % wet basis (w.b) as determined by standard oven tests (ASAE 1994c). The wheat moisture content was 9.2 % (w.b) determined according to this standard procedure. These values of moisture content are typical for good post-harvest storage conditions for grain after the drying operation. Moisture content was kept at these equilibrium values to assure the stability of the moisture content of the grain particles.

Samples of both corn and wheat were ground to three different particle sizes. The operation consisted more of chopping than of grinding, since a simple Osterizer™ home blender was used. The resulting mixture was a combination of particles of different sizes ranging from fine powder to half-kernel particles. Various residence times in the blender were used to obtain different particle size distributions. The three size distributions for corn were designated C10, C30, and C60 (where 10, 30, and 60 represent chopping time in seconds); whereas for wheat, W24, W45, and W80 represent samples chopped for 24, 45 and 80 s, respectively. A 150 g sample of material was chopped for each sample, out of which 50 g was rapidly sealed in sample bottles and kept at 4°C until 12 h before dielectric properties measurement. The remaining 100 g quantity of each sample was used in the sieving test to determine the particle size distribution. The sieves used were U.S. Std.# 4, 8, 12, 20, 35, 60, and 140 for corn and U.S. Std.# 12, 20, 35, 60, and 140 for wheat. A suitable mechanized sieve (Ro-tap[R], Testing Sieve Shaker, CE Tyler, Tyler Company of Canada, Toronto, ON) was used. The time of shaking and method of data analysis was that prescribed by ASAE Standard S319.2 (ASAE 1994b). After completion of the appropriate shaking time, the residual amounts in each sieve were weighed and the material was put in sample bottles and kept at 4°C until 12 h before measurement of dielectric properties. These bottles were labelled according to the type of grain and the sieve number. For example, CS 12 refers to corn taken from sieve #12 and WP the residual weight fraction of wheat . Only one set of such bottles was filled for each kind of grain. Because the grain came from a unique source, there should not have been significant differences between sieved material from different batches.

As a point of reference, samples of whole kernels of both kinds of grains were also stored in the same type bottles for later measurements. They were labelled WGC for Whole Grain Corn and WGW for Whole Grain Wheat. All the bottles were stored at 4°C for 12 h before the measurements at which time they were allowed to warm to room temperature gradually in order to avoid condensation in the bottles. Kernel density was calculated by measuring the volume of water displaced by a known mass of kernels. An average over 10 readings resulted in a value of 1.193 Mg/m^3 for corn and 1.187 Mg/m^3 for wheat. These tests were done rapidly to avoid any moisture uptake by the kernels and no air bubbles were observed inside the graduated glass tube. As a result of these procedures, the set of samples for which dielectric properties measurements were to be obtained consisted of 3 samples of different particle size distribution, 1 sample of whole kernels, and 5 and 7 samples of wheat and corn, respectively, with grain particles of a homogeneous size. In total, dielectric properties were taken on 20 samples at different densities. All measurements were done at 915 MHz frequency and 24°C using a TM_{010} cavity. The sample holder consisted of a Teflon cup machined to fit the cavity to withstand the pressure required in compressing samples to 1.0 Mg/m^3 bulk density. At this density, a straight line of sufficient reliability would allow extrapolation of the functions of dielectric properties to obtain the properties corresponding to whole kernel density.

Initially, the sample holder was filled loosely and a sample height gauge made of a calibrated steel rod was inserted to form a plane surface at the top of the material. The scale scribed on the rod corresponded directly to the volume of the sample, which was calculated as the inside cross sectional area times the length. The steel rod, as mentioned above, was also used to pack the particulates in the Teflon cylindrical section (d = 12mm) which represented the sample holder. The height of the sample holder was slightly greater than 40 mm to meet the minimum required height of the perturbing resonant cavity of 40 mm, excluding the thickness of the wall metal. Volume of the empty cavity was much greater (> 1000 times) than the volume of the sample.

Cavity transmission measurements were made with a computer controlled Hewlett-Packard Model 8753 Network Analyzer (Fig 1). One of the test ports of the network analyzer was connected with the resonant copper cavity (TM_{010} mode) through standard N-type coaxial connectors. A 'marker-to-maximum' command on a network analyzer automatically accomplished determination of the coordinates of the peak of the resonant curve, with and without an object (dielectric, sample) in the cavity, providing all the information necessary to determine the main circuit parameters, as discussed earlier (Venkatesh 1996).

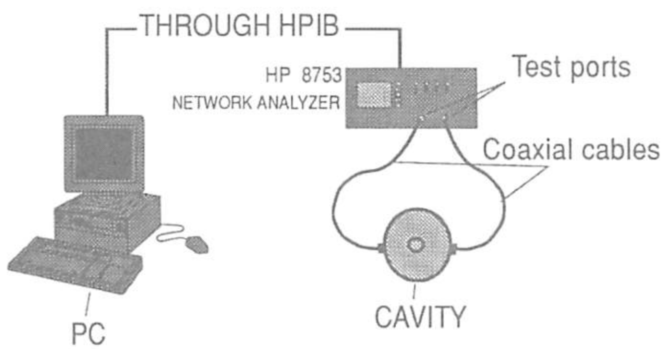

Fig. 1. Schematic diagram of the measurement setup.

Table I. Dielectric constants ε' and dielectric loss factor ε" of chopped corn sample with corresponding bulk densities.

Density (Mg/m^3)	ε'	ε'
0.585	2.51	0.2721
0.618	2.51	0.2772
0.619	2.79	0.3425
0.758	3.04	0.4112
0.904	3.75	0.6099
0.951	4.15	0.7263
1.058	4.88	0.9507
1.102	5.24	1.0552

Table II. Coefficients of regression model relating the dielectric constant ϵ'_r to the density ρ for corn at 24 °C and 915 MHz frequency.

		$\epsilon_r' = (A_o+A_1\rho)^2$				$\epsilon_r' = (A_o + A_1\rho)^3$			
Sample	Density range (Mg/m^3)	A_o	A_1	r^2	s.e	A_o	A_1	r^2	s.e
C1	0.585-1.102	0.9236	1.1612	0.977	0.0635	0.9716	0.6636	0.989	0.0254
C2	0.622-1.122	0.9413	1.1764	0.988	0.0479	0.9804	0.6709	0.996	0.0164
C3	0.650-1.111	0.9488	1.1919	0.988	0.0459	0.9839	0.6810	0.996	0.0152
WGC	0.534-0.807	0.9988	1.1937	1.000	0.0064	1.0037	0.7076	0.999	0.0062
CS4	0.507-0.747	0.9927	1.1400	0.997	0.0185	0.9994	0.6818	0.998	0.0082
CS8	0.611-0.898	0.9879	1.1273	0.997	0.0184	0.9983	0.6643	0.999	0.0061
CS12	0.582-0.885	0.9775	1.1088	0.993	0.0288	0.9925	0.6547	0.997	0.0108
CS20	0.660-0.964	0.9604	1.0260	0.977	0.0583	0.9818	0.6052	0.985	0.0273
CS35	0.528-1.003	0.9492	1.0552	0.986	0.0415	0.9800	0.6171	0.993	0.0171
CS60	0.523-1.026	0.9694	1.0450	0.996	0.0218	0.9939	0.6076	0.999	0.0066
CS140	0.378-0.992	0.9576	1.0383	0.994	0.0267	0.9884	0.6046	0.998	0.0089

RESULTS AND DISCUSSION

Data, as illustrated in Table 1, for one sample were obtained for all samples of corn and wheat. Linear regressions were calculated for the following models :

$$\left(\varepsilon_{est}'\right)^{1/2} = A_0 + A_1\rho \qquad (10)$$

$$\left(\varepsilon_{est}'\right)^{1/3} = A_0 + A_1\rho \qquad (11)$$

where:

A_o, A_1 = regression coefficients, and
subscript "est" = regression estimates (not to confuse with the relative dielectric constant).

The coordinate (0,1) was included in the data for all regressions to account for the dielectric constant of air when the sample holder is empty. The results of the regressions are listed in Tables II and III where the regression coefficients A_o and A_1 appear, as well as the values of the coefficient of determination r^2, and the standard error of estimate s.e based on the residuals. Most of the values obtained for A_o, the axis intercept, are close to the theoretical value of 1. Inclusion of the coordinate /intercept (0,1) emphasizes the similarity between the regression models and the theoretical models in Eqs. 4 and 5. The cubic root model seems to better represent the phenomenon as earlier reported by Nelson and You (1989). The r^2 values were also higher for the cube root model. The reliability of these straight lines made it possible to extrapolate for the dielectric constant at densities outside the range of measurements.

Table III. Coefficients of regression model relating the dielectric constant ϵ'_r to the density ρ for wheat at 24 °C and 915 MHz frequency.

		$\epsilon_r' = (A_o+A_1\rho)^2$				$\epsilon_r' = (A_o + A_1\rho)^3$			
Sample	Density range (Mg/m^3)	A_o	A_1	r^2	s.e	A_o	A_1	r^2	s.e
W1	0.726-1.090	0.9744	0.9326	0.990	0.0320	0.9917	0.5477	0.994	0.0142
W2	0.680-1.056	0.9809	0.9152	0.995	0.0217	0.9949	0.5412	0.998	0.0078
W3	0.670-1.052	0.9738	0.9489	0.992	0.0270	0.9917	0.5586	0.997	0.0101
WWG	0.707-1.004	0.9873	0.8962	0.995	0.0266	0.9957	0.5345	0.998	0.0103
WS12	0.668-0.981	0.9907	0.9205	0.998	0.0166	0.9980	0.5495	1.000	0.0042
WS20	0.670-0.996	0.9888	0.9179	0.996	0.0232	0.9968	0.5486	0.998	0.0090
WS35	0.596-0.988	0.9705	0.9172	0.990	0.0336	0.9886	0.5452	0.996	0.0103
WS60	0.475-1.088	0.9631	0.9152	0.992	0.0255	0.9875	0.5416	0.997	0.0042
WS140	0.618-1.024	0.9786	0.8856	0.994	0.0206	0.9936	0.5274	0.998	0.0090
WP	0.459-0.812	0.9834	0.8448	0.993	0.0204	0.9938	0.5146	0.997	0.0132

Table IV. Coefficients of regression model relating the dielectric constant ϵ''_r to the density ρ for wheat at 24 °C and 915 MHz frequency.

		$(\epsilon_r'') = A_o+A_1\rho+A_2\rho^2$				$(\epsilon_r''+e) = (A_o + A_1\rho)^2$			
Sample	Density range (Mg/m^3)	A_o	A_1	A_2	r^2	A_o	A_1	r^2	s.e
C1	0.585-1.102	0.0073	-0.2391	1.0587	0.994	-0.0207	0.9259	0.994	0.0255
C2	0.622-1.122	0.0018	-0.1672	0.9973	0.998	-0.0165	0.9265	0.998	0.0158
C3	0.650-1.111	0.0022	-0.1946	1.0856	0.998	-0.0156	0.9568	0.998	0.0166
WGC	0.534-0.807	-0.0009	0.1825	0.7431	0.996	0.0102	1.0016	0.997	0.0170
CS4	0.507-0.747	0.0007	0.0596	0.8627	0.997	0.0045	0.9723	0.999	0.0104
CS8	0.611-0.898	0.0000	-0.0167	0.9336	0.998	-0.0036	0.9291	0.999	0.0075
CS12	0.582-0.885	0.0000	-0.1239	0.9747	0.982	-0.0078	0.9144	0.998	0.0116
CS20	0.660-0.964	-0.0011	-0.1117	0.9384	0.995	-0.0074	0.9083	0.997	0.0169
CS35	0.528-1.003	0.0001	-0.0252	0.7865	0.999	-0.0032	0.8734	1.000	0.0057
CS60	0.523-1.026	0.0006	0.0068	0.7030	0.999	-0.0021	0.8415	1.000	0.0051
CS140	0.378-0.992	0.0053	0.0422	0.6387	0.999	-0.0223	0.8114	0.996	0.0157

A similar approach was taken to examine the relationship between the relationship for ϵ_{est}'' and ρ. In this case, however, only the square root model was used. To compute e in Eq. 5, the following regression equation was obtained :

$$\varepsilon_{est}'' = A_0 + A_1\rho + A_2\rho^2 \quad (12)$$

Coefficients for Eq.12 are listed in Tables IV and V. The coordinate (0,0) was included in all regressions. The values obtained for A_o are nearly zero and therefore negligibly small for all samples. Thus, Eq. 12 becomes similar to Eq. 8 and the value of e for use in Eq. 5 can be determined by Eq. 9. The regression of $(\epsilon''+e)^{1/2}$ on density ρ, can be calculated by :

$$(\varepsilon_{est}''+e)^{1/2} = A_0 + A_1\rho \quad (13)$$

Table V. Coefficients of regression model relating the dielectric constant ϵ''_r to the density ρ for wheat at 24 °C and 915 MHz frequency.

Sample	Density range (Mg/m³)	$(\epsilon_r'') = A_o+A_1\rho+A_2\rho^2$ A_o	A_1	A_2	r^2	$(\epsilon_r''+e) = (A_o+A_1\rho)^2$ A_o	A_1	r^2	s.e
W1	0.726-1.090	-0.0024	-0.0143	0.4971	0.963	-0.0055	0.6973	0.987	0.0269
W2	0.680-1.056	-0.0006	-0.0117	0.4850	0.997	-0.0023	0.6888	0.999	0.0076
W3	0.670-1.052	0.0009	-0.0391	0.5603	0.997	-0.0027	0.7228	0.998	0.0090
WGW	0.707-1.004	0.0003	-0.0541	0.5450	0.999	-0.0123	0.6256	0.990	0.0123
WS12	0.668-0.981	-0.0002	0.0581	0.4666	1.000	0.0033	0.7301	1.000	0.0063
WS20	0.670-0.966	0.0000	-0.0244	0.5546	0.996	-0.0013	0.7263	0.999	0.0104
WS35	0.596-0.988	0.0011	-0.0142	0.5178	0.995	0.0004	0.7083	0.997	0.0143
WS60	0.475-1.088	0.0012	0.0235	0.4628	0.998	0.0081	0.6938	0.998	0.0092
WS140	0.618-1.024	0.0002	-0.0297	0.5029	0.987	-0.0032	0.6878	0.999	0.0058
WP	0.459-0.812	0.0010	-0.0710	0.3700	0.996	-0.0122	0.6805	0.994	0.0149

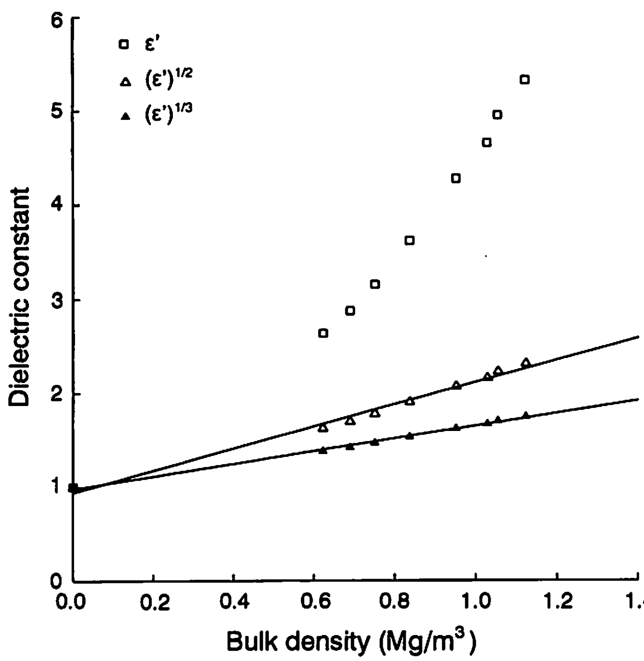

Fig. 2. Dielectric constant vs bulk density for corn C30 sample. The straight lines represent functions extrapolated to 1.3 Mg/m³.

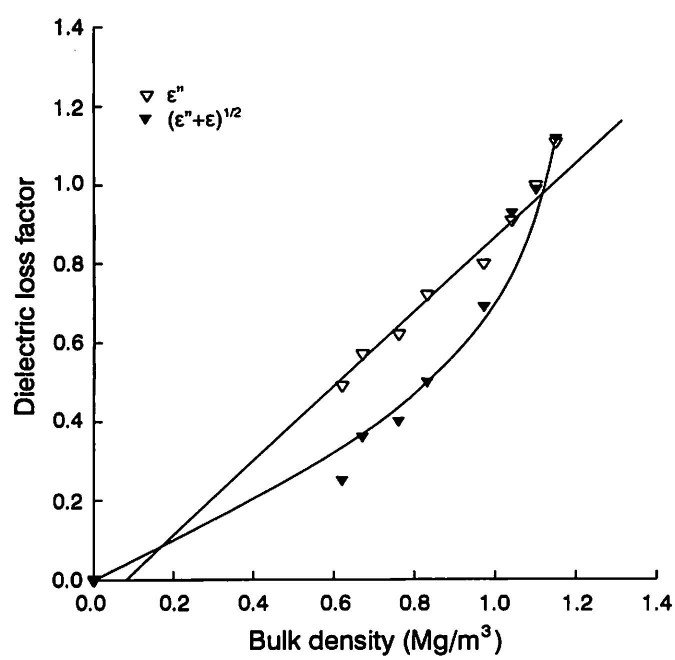

Fig. 3. Dielectric loss factor vs bulk density for corn C30 sample. The straight lines represent functions extrapolated to 1.3 Mg/m³.

The regression coefficients for this straight line are listed in Tables IV and V. For the ϵ_{est}'' vs ρ relationship, the values of A_0 are close to the expected point. The r^2 values also indicate a good reliability of the straight lines for all samples. Figures 2 to 5 illustrate the results of the density effect on the quadratic and cubic functions of the dielectric properties for corn (C30) and wheat (WS60) samples chosen arbitrarily.

PARTICLE SIZE EFFECT

The possibility that there is a particle size effect on the dielectric properties of corn and wheat was investigated. In the case of corn (Fig. 6), the material that was ground for the shortest time (C10) and had a coarser particle size distribution (Fig. 7), exhibits steeper slopes of both dielectric properties as functions of bulk density. Moreover, the curve is displaced vertically towards higher values than are those of the two

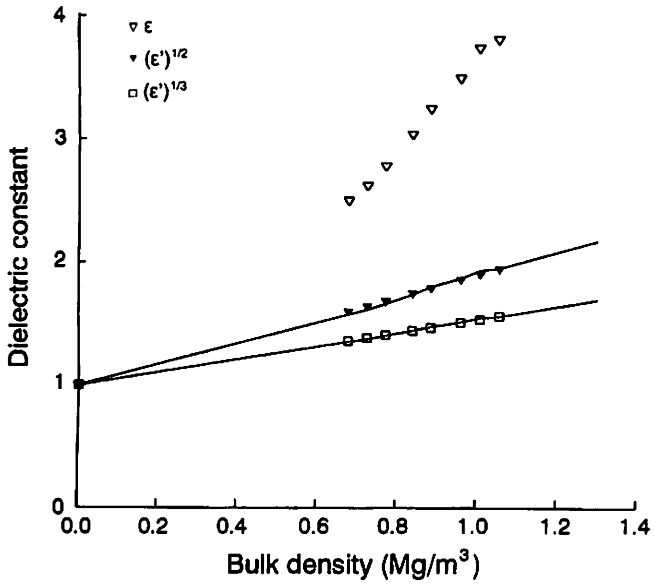

Fig. 4. Dielectric constant vs bulk density for corn WS60 sieved sample. The straight lines correspond to regression functions extrapolated to 1.3 Mg/m³.

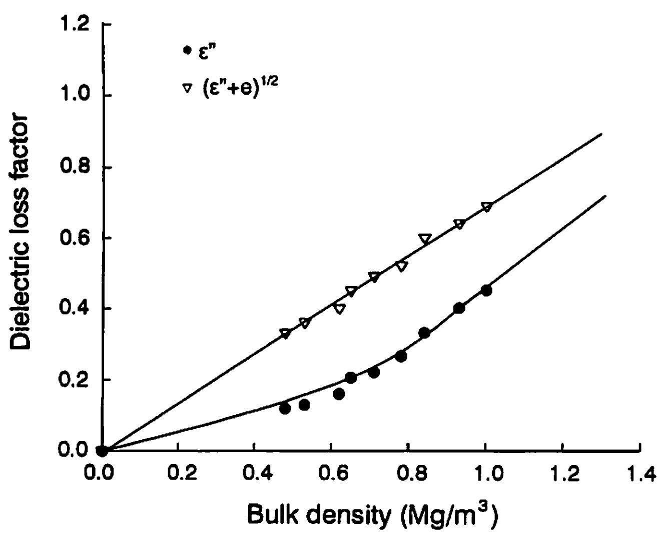

Fig. 5. Dielectric loss factor vs bulk density for corn WS60 sieved sample. The straight line is the regression extrapolated to 1.3 Mg/m³.

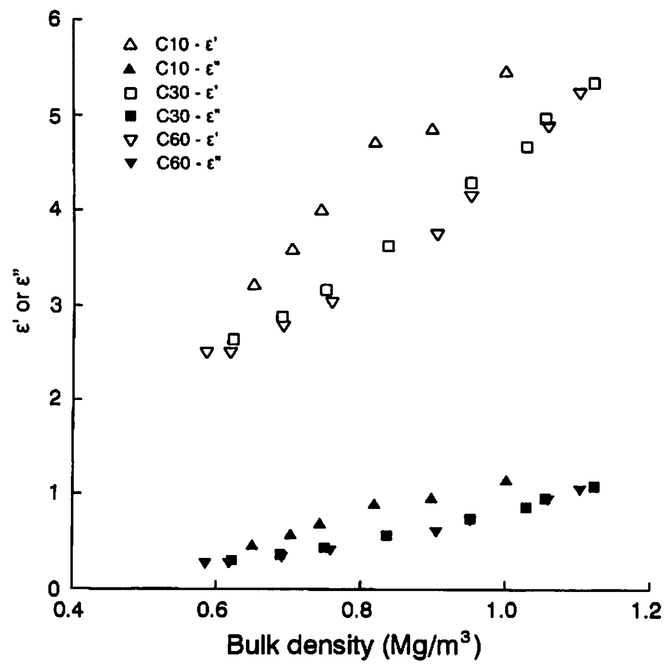

Fig. 6. Dielectric properties of various particle-size distributions of corn at different bulk densities at room temperature (24 °C) and 915 MHz frequency.

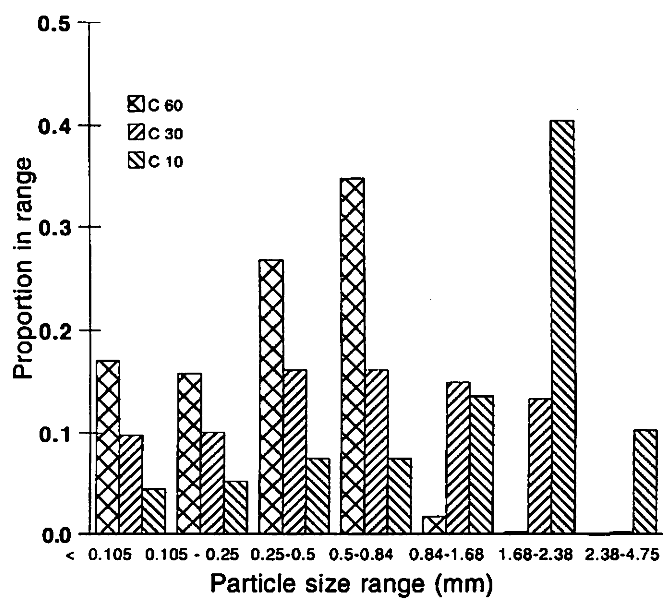

Fig. 7. Particle size range (mm) and proportion of three ground corn samples (C10, C30, C60).

finer sample types, which exhibit similar slopes for both the dielectric constant and dielectric loss. The raw data indicated that 0.4, 0.6, and 1.0 g moisture were lost from C10, C30, and C60, respectively, all having started at 100 g initial mass. Since these moisture losses are small, they cannot fully account for the observed differences in dielectric properties (see moisture relations in Nelson 1984a, 1984b). It should be noted that the values of the dielectric properties of the coarser sample at 0.75 Mg/m³ are at least 10% greater than values given in the literature (ASAE 1994a) for whole kernels of about the same density, whereas the finer samples seem to agree well. Although others have reported measurement errors of the order of 2-15% (Trabelsi et al. 1997; Kraszewski et al. 1995), it is difficult to explain why the coarser sample would have a constant positive error over several measurements at different densities. We do not discount the possibility that the error is actually one of underestimation of the bulk density of the coarser sample. Also, differences with values reported by others could be due to compositional differences between the hybrids used here and in other work.

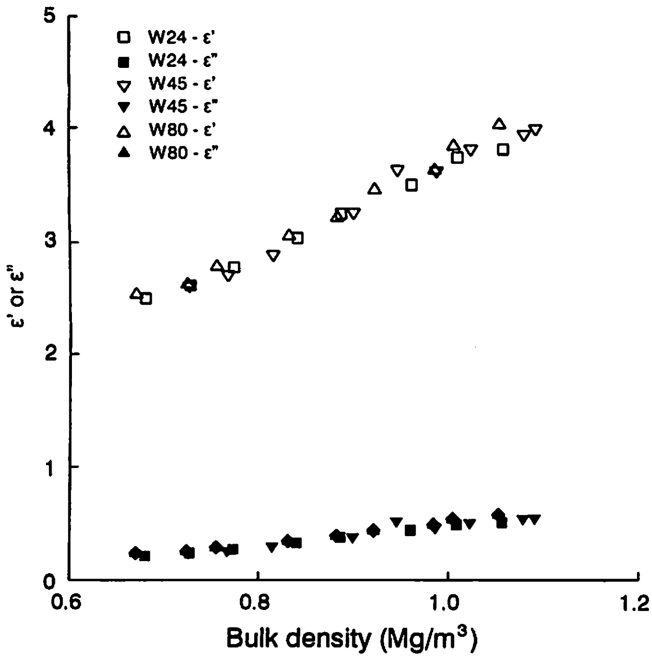

Fig. 8. Dielectric properties of various particle-size distributions of wheat at different bulk densities at room temperature (24 °C) and 915 MHz frequency.

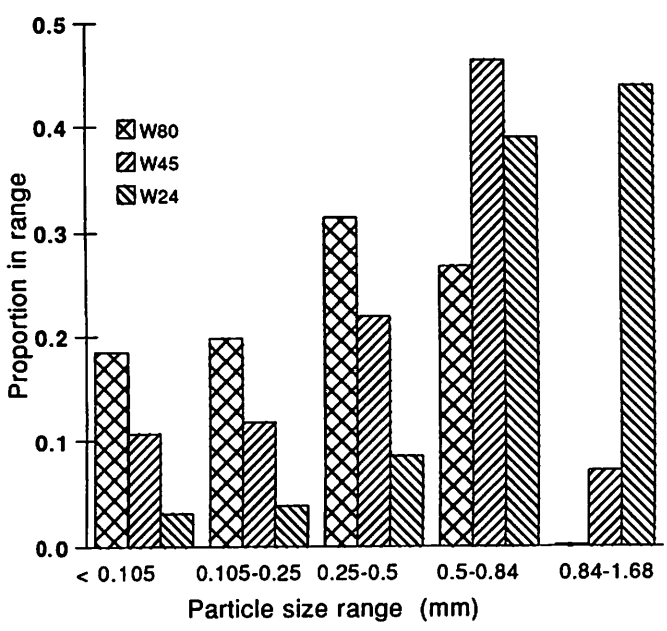

Fig. 9. Particle-size range (mm) and proportion of three ground wheat sanples (W24, W45, W80).

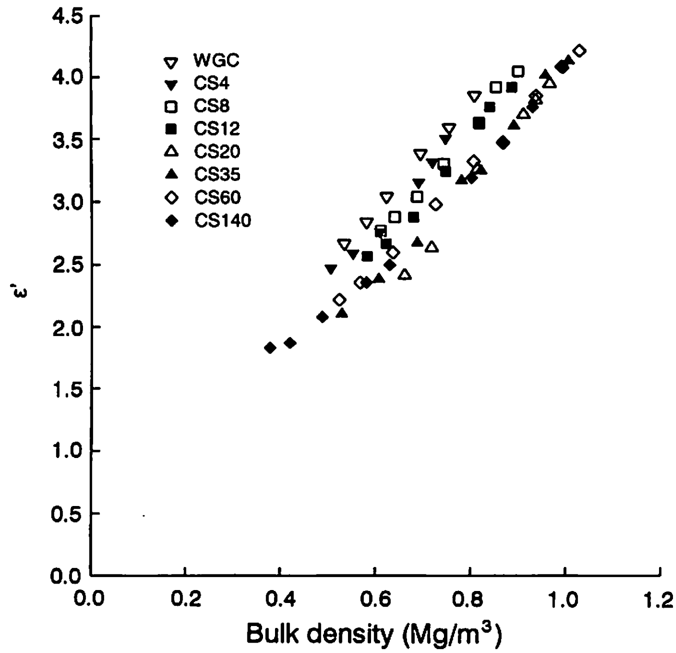

Fig. 10. Dielectric constant of various size fractions of corn as a function of bulk density.

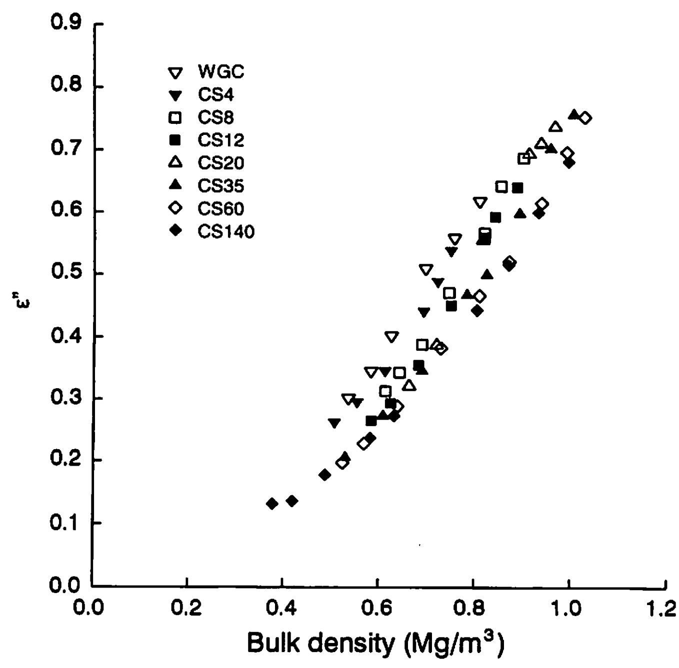

Fig. 11. Dielectric loss factor of various size fractions of corn as a function of bulk density.

In the case of wheat (Fig. 8), the moisture losses for W24, W45, and W80 were 0.39, 0.67, and 0.76 g, respectively, also for initial masses of 100 g. Here, the dielectric properties appear to be completely independent of the particle size distributions as shown in Fig. 9. The dielectric constant and loss factor of wheat at 0.75 Mg/m^3 correspond well with the data in the literature (Nelson 1982; ASAE 1994a).

Figures 10 and 11 show the dielectric constant and loss factor for different size fractions of corn after sieving and compression to various bulk densities with whole grain corn as a reference (WGC). In the case of wheat, the differences are evidently smaller and not significantly different from the values for the whole wheat kernels (Figs. 12, 13). The highest curves for both ϵ' and ϵ" for corn correspond to whole grain. Here, it appears that there are differences related to particle size.

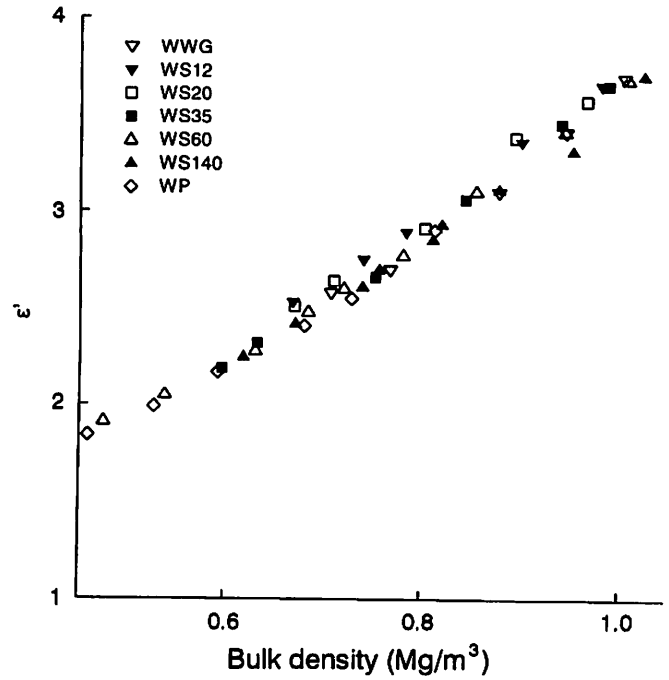

Fig. 12. Dielectric constant of various size fractions of wheat as a function of bulk density.

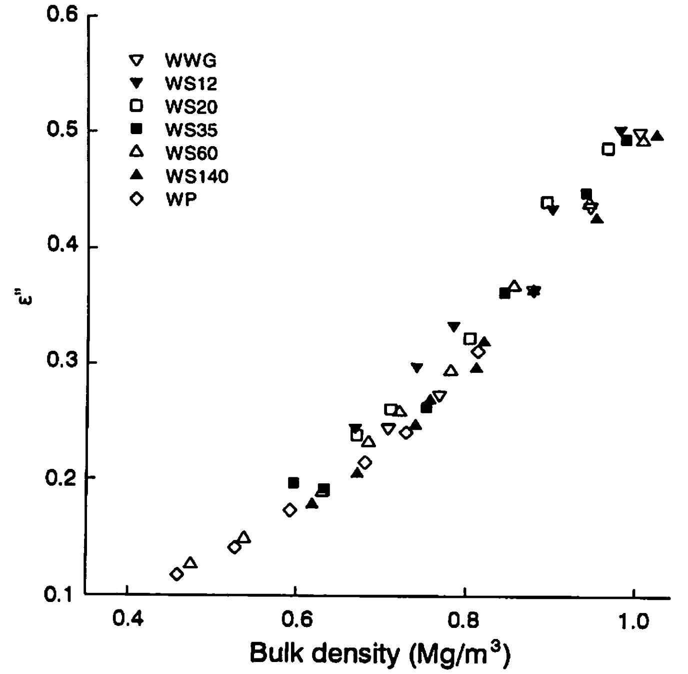

Fig. 13. Dielectric loss factor of various size fractions of wheat as a function of bulk density.

However, the moisture contents of each sieve fraction were not determined, nor were the chemical compositions. Thus, the differences cannot be conclusively attributed to particle size.

CONCLUSION

Existing models (Nelson 1983a, 1983b, 1991) of dielectric properties as functions of the bulk density of air-particle mixtures were validated for whole corn and wheat kernels as well as for chopped and powdered forms. A preliminary investigation into the possible effects of particle size on bulk dielectric properties of grains suggested that breakage of non-homogeneous materials could affect the dielectric response to a certain extent for corn; however, there is insufficient supporting data to definitely confirm this possibility. The range of response attributable to particle size was greater for corn than for wheat which showed no particle size dependence. For corn, it is not likely that differences in moisture content between the different size fractions could explain the variations in dielectric response. Compositional differences and errors due to methods may be involved.

ACKNOWLEDGEMENTS

The experimental work was supported by the Formation des Chercheurs et l'Aide a la Recherche (FCAR) grant provided by the Ministry of Education, Quebec and by a Natural Science and Engineering Research Council (NSERC) grant. The authors acknowledge Ms. V. Orsat for editorial help.

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