MICROWAVE DIELECTRIC PROPERTIES OF CEREAL GRAINS

S. Trabelsi, S. O. Nelson

ABSTRACT. *Dielectric properties of five cereal grains (wheat, corn, barley, oats, and grain sorghum) were measured at 23°C over a range of moisture contents and over microwave frequencies from 5 to 15 GHz with a free-space transmission technique. Resulting dielectric constants and loss factors are tabulated for each material for moisture ranges of interest to the grain industry at bulk densities that are close to the corresponding test weight of those cereal grains. Bulk densities of all grain lots decreased linearly with increasing moisture content. Both the dielectric constant and loss factor of all grain lots increased nearly linearly with increasing moisture content at all frequencies. For given moisture contents, the dielectric constants of all grains tested decreased with increasing frequency, and the loss factor changed relatively little over the frequency range. The new data will be useful in grain moisture sensing work and in microwave heating applications.*

Keywords. *Attenuation, Bulk density, Dielectric constant, Dielectric loss factor, Free space, Grain, Microwave, Moisture, Phase shift, Transmission.*

Dielectric properties of materials represent their intrinsic electrical signature. They characterize the interaction between the electric field and the material. Measurement of the dielectric properties of moist granular materials such as cereal grain and oilseed is essential for understanding their electrical behavior (Nelson, 1973a) and for the development of reliable, indirect, nondestructive sensing methods for determining their physical characteristics including moisture content and bulk density (Kraszewski et al., 1997; Trabelsi et al., 1997b; Bartley et al., 1998; Archibald et al., 1998). Knowledge of dielectric properties is also important in radio-frequency (RF) and microwave heating applications (Nelson, 1985, 1987). For better modeling of the electrical behavior of these materials and effective use of the dielectric properties in industrial applications, these properties have to be measured accurately over a broad frequency range. Dielectric properties are, by definition, a measurement of the polarizability of a material when subjected to an electric field. For lossy materials, the dielectric properties are represented by the relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$, where ε' is the dielectric constant, ε'' is the dielectric loss factor, and j is the imaginary unit ($j = \sqrt{-1}$). The dielectric constant represents the capability of a material to store electric energy, and the dielectric loss factor represents its ability to dissipate the electric-field energy as heat.

Dielectric properties of liquid water are well described by the Debye model (Hasted, 1973) and show a single dipolar relaxation at about 17.9 GHz at 22°C (Kaatze, 1989). However, those of bound water, which is encountered in many foods and agricultural products, lie somewhere between those of ice and those of liquid water, depending on the degree of binding. There is no physical model that fully describes the behavior of bound water in moist substances.

At radio frequencies, dielectric properties of cereal grain depend on frequency, moisture content, bulk density, and temperature (Kraszewski et al., 1996; Nelson, 1973a, 1973b; Nelson and Stetson, 1976; Trabelsi et al., 1997a). Dielectric data for grain and seed are reported in the literature (Nelson, 1973a; Tinga and Nelson, 1973; Kent, 1987), but those measured above 2.45 GHz are limited (*ASAE Standards*, 2002). Very often, the data available are given at a single frequency for a limited range of bulk densities and moisture contents. In this study, dielectric properties of five cereal grains were measured with a free-space transmission technique with a single measurement setup consisting of a pair of horn-lens antennas connected to a vector network analyzer for frequencies ranging from 5 to 15 GHz. Dielectric constants and loss factors of wheat, corn, barley, oats, and grain sorghum were measured at 23°C for moisture ranges of interest to the grain industry and bulk densities similar to the test weight of each material. Results of the measurements are tabulated in this article. The dielectric properties data reported in this article were used in the development of models for the microwave dielectric properties of cereal grains (Nelson and Trabelsi, 2011), which have now been included in the ASABE Standards (*ASABE Standards*, 2012).

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Materials and Methods

Sample Preparation

Samples of five cereal grains, including wheat ('Arapahoe' hard red winter wheat, *Triticum aestivum* L.), corn (Pioneer 3335 hybrid yellow-dent field corn, *Zea mays* L.), barley ('Canlon' spring barley, *Hordeum vulgare* L.), oats ('Chapman' winter oats, *Avena sativa* L.), and grain sorghum (*Sorghum bicolor* L.), of different moisture contents were prepared by spraying distilled water on these samples to bring them to the desired moisture level. For each material, the sample consisted of about 7 kg of material. After adding the proper amount of water, the sample was mixed to distribute the water more evenly throughout the sample. The samples were then placed in sealed bags and stored for at least 72 h at 4°C to equilibrate. During this time, the samples were occasionally mixed within the sealed bags to aid uniform moisture distribution. For each material, the sample moisture covered a range of interest to the grain industry. The samples were removed from cold storage and allowed to equilibrate to room temperature (23°C) for 24 h before measurement of their dielectric properties.

Free-Space Measurement of Dielectric Properties of Grain

Different measurement techniques can be used for measurement of the relative complex permittivity of materials at microwave frequencies (Von Hippel, 1954). A free-space transmission technique was selected because the information collected is relative to the entire volume of the sample interacting with the incident electric field of the propagating electromagnetic wave, which makes the measured dielectric properties more representative of the sample material. Other advantages of this measurement technique include the facts that it does not require physical contact with the material and the sample preparation is minimal. Basically, the sample was placed in a Styrofoam container between two horn-lens antennas facing each other (Trabelsi and Nelson, 2003) (fig. 1). Styrofoam was selected because it has a dielectric constant close to that of air, about 1.03, and thus its contribution to the reflection coefficient at the air-sample interface is negligible. For each sample, the dielectric properties were determined from measurement of the attenuation (ΔA) and phase shift ($\Delta\phi$) that the incident electromagnetic wave undergoes when traversing the layer of material. The attenuation amounts to energy loss in the material, while the phase shift is related to the slowing of the wave velocity inside the material. For better accuracy, two horn-lens antennas providing a focused beam were used, and the effect of multiple reflections was minimized by selecting appropriate sample thickness. In addition, time-domain gating was applied to filter out undesirable post-calibration mismatches.

The dielectric properties (ε' and ε'') were determined, assuming a plane wave propagating through a low-loss material ($\varepsilon'' << \varepsilon'$), with the following equations (Nyfors and Vainikainen, 1989):

$$\varepsilon' = \left[1 - \frac{(\Delta\phi - 360n)}{360d}\frac{c}{f}\right]^2 \tag{1}$$

$$\varepsilon'' = \frac{-\Delta A}{8.686\pi d}\frac{c}{f}\sqrt{\varepsilon'} \tag{2}$$

where c is the speed of light (m s^{-1}), f is the frequency (Hz), d is the thickness of the layer of material (m), and n is an integer to be determined (Trabelsi et al., 2000). Granular

Figure 1. Measurement setup (radiation-absorbing material not shown).

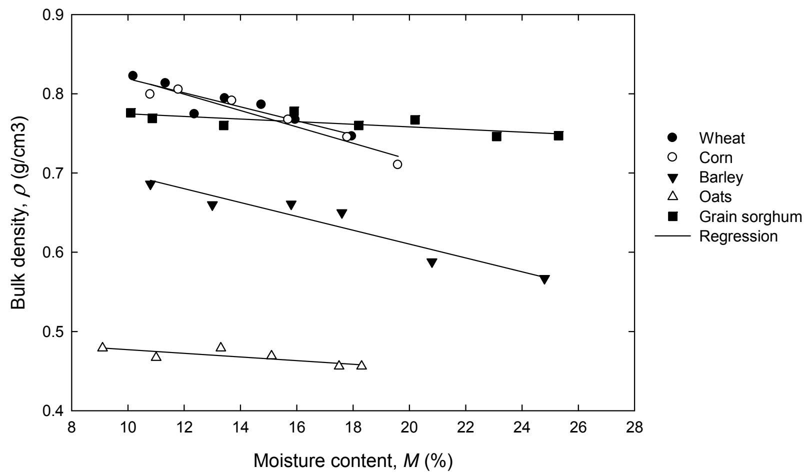

Figure 2. Variation of bulk density with moisture content for wheat, corn, barley, oats, and grain sorghum.

materials such as cereal grains can be described as mixtures composed of solid particles and air. Mixture equations were applied to model the dielectric behavior of powdered and granular materials (Nelson, 1983, 2005). The dielectric properties presented in this article for each material are the effective dielectric properties of the mixture.

The measurement setup is illustrated in figure 1. It consists of a Hewlett-Packard 8510C vector network analyzer (VNA), a computer, two high-quality coaxial cables with APC-7 connectors at their terminations, two linearly polarized, ultrabroadband (2 to 26 GHz) horn-lens antennas (model AHO-2077-N, BAE Systems, London, U.K.), a Styrofoam sample holder, and four sheets of radiation-absorbing material (Eccosorb AN-79, Emerson and Cuming Microwave Products, Randolph, Mass.). A special wooden structure was made to hold the antennas in place and keep them well aligned. The VNA was used for measurement of attenuation (ΔA) and phase shift ($\Delta\phi$). It was calibrated between 2 and 18 GHz with a response-type calibration in which the reference value for attenuation and phase shift was set at zero with an empty sample holder between the two antennas. For each sample, attenuation and phase measurements were performed between 2 and 18 GHz with an increment of 1 GHz. The whole measurement procedure was automated and controlled by a computer connected to the VNA.

Errors in free-space measurements are often related to the nonplanar nature of the electromagnetic wave, multiple reflections within the sample and between the antennas, reflections from the surroundings, post-calibration mismatches, and possible multiple-path transmissions (Chen et al., 2004; Kraszewski et al., 1996; Trabelsi et al., 1998a; Trabelsi and Nelson, 2003, 2006). In this study, improvements of a free-space transmission technique for measurements between 2.0 and 18.0 GHz were made by using horn-lens antennas, selecting the optimum thickness for each sample, and applying time-domain gating (Trabelsi and Nelson, 2003). The horn-lens antennas collimate the electromagnetic energy in a rela-

Table 1. Dielectric constant (ε′) and loss factor (ε″) of wheat at 23°C and indicated moisture contents and bulk densities.

Frequency (GHz)	Dielectric Properties	Moisture Content (M, %) and Bulk Density (ρ, g cm^{-3})						
		M = 10.2, ρ = 0.822	M = 11.34, ρ = 0.813	M = 12.37, ρ = 0.774	M = 13.45, ρ = 0.794	M = 14.75, ρ = 0.786	M = 15.95, ρ = 0.767	M = 17.96, ρ = 0.746
5	ε′	2.62	2.68	2.65	2.74	2.87	2.86	3.07
	ε″	0.23	0.26	0.30	0.34	0.37	0.43	0.48
6	ε′	2.59	2.65	2.61	2.70	2.81	2.81	2.98
	ε″	0.23	0.26	0.30	0.34	0.37	0.43	0.49
7	ε′	2.57	2.62	2.59	2.67	3.05	2.78	2.92
	ε″	0.23	0.26	0.30	0.33	0.45	0.43	0.50
8	ε′	2.55	2.61	2.58	2.66	2.74	2.75	2.89
	ε″	0.23	0.26	0.29	0.33	0.37	0.43	0.50
9	ε′	2.53	2.59	2.56	2.64	2.71	2.73	2.86
	ε″	0.24	0.26	0.28	0.33	0.37	0.42	0.52
10	ε′	2.51	2.57	2.54	2.62	2.69	2.71	2.82
	ε″	0.24	0.26	0.27	0.32	0.37	0.41	0.53
11	ε′	2.50	2.56	2.53	2.59	2.67	2.69	2.78
	ε″	0.24	0.26	0.27	0.31	0.37	0.40	0.53
12	ε′	2.49	2.55	2.52	2.58	2.65	2.67	2.77
	ε″	0.23	0.26	0.26	0.31	0.37	0.39	0.53
13	ε′	2.49	2.55	2.51	2.57	2.64	2.65	2.76
	ε″	0.23	0.25	0.26	0.30	0.36	0.38	0.52
14	ε′	2.49	2.54	2.50	2.56	2.64	2.64	2.75
	ε″	0.22	0.25	0.26	0.30	0.36	0.38	0.52
15	ε′	2.48	2.53	2.49	2.55	2.64	2.63	2.74
	ε″	0.22	0.25	0.26	0.30	0.36	0.37	0.53

Table 2. Dielectric constant (ε′) and loss factor (ε″) of corn at 23°C and indicated moisture contents and bulk densities.

Frequency (GHz)	Dielectric Properties	Moisture Content (M, %) and Bulk Density (ρ, g cm^{-3})					
		M = 10.8, ρ = 0.799	M = 11.8, ρ = 0.805	M = 13.7, ρ = 0.791	M = 15.7, ρ = 0.767	M = 17.8, ρ = 0.745	M = 19.6, ρ = 0.710
5	ε′	2.68	2.81	2.94	3.06	3.36	3.43
	ε″	0.30	0.33	0.42	0.49	0.66	0.72
6	ε′	2.65	2.76	2.87	3.00	3.22	3.32
	ε″	0.31	0.34	0.44	0.51	0.70	0.76
7	ε′	2.64	2.73	2.81	2.95	3.16	3.29
	ε″	0.31	0.35	0.44	0.53	0.67	0.78
8	ε′	2.64	2.72	2.80	2.92	3.14	3.18
	ε″	0.31	0.36	0.45	0.56	0.70	0.79
9	ε′	2.62	2.69	2.77	2.88	3.08	3.13
	ε″	0.31	0.37	0.47	0.58	0.72	0.81
10	ε′	2.60	2.67	2.74	2.86	3.05	3.08
	ε″	0.31	0.39	0.50	0.61	0.72	0.83
11	ε′	2.59	2.65	2.70	2.83	3.01	3.03
	ε″	0.32	0.40	0.51	0.64	0.73	0.84
12	ε′	2.58	2.65	2.70	2.82	2.98	3.00
	ε″	0.33	0.41	0.51	0.66	0.75	0.86
13	ε′	2.56	2.64	2.69	2.80	2.97	2.97
	ε″	0.34	0.42	0.51	0.67	0.75	0.88
14	ε′	2.56	2.64	2.69	2.80	2.97	2.95
	ε″	0.35	0.43	0.52	0.69	0.79	0.92
15	ε′	2.57	2.64	2.70	2.80	2.91	2.91
	ε″	0.38	0.44	0.53	0.70	0.84	0.98

tively narrow beam and provide a plane wave a short distance from the transmitting antenna. This allowed measurements on samples of reasonable size in the far field without problems of edge diffraction or interference by reflections from the surroundings (Chen et al., 2004). To further isolate the sample from the surroundings, the sample was placed in a tunnel-shaped enclosure made of a radiation-absorbing material (Eccosorb AN-79, 11.4 cm thick) that surrounded the space between the transmitting and receiving antennas (fig. 1). For each sample of a given moisture content, the sample thickness was judiciously selected to ensure at least a one-way 10-dB attenuation to minimize effects of multiple reflections and to remain within the dynamic range of the VNA. Sample thicknesses ranged between 5 and 15 cm for satisfying these criteria. Finally, for each sample, time-domain gating was applied to the main transmission response to remove undesirable effects of post-calibration mismatches and possible multiple-path transmission (Trabelsi and Nelson, 2003).

Measurement Procedure

For each sample, preliminary measurements were performed to determine the thickness that allowed optimum use of the VNA over the selected frequency range with an

Table 3. Dielectric constant (ε′) and loss factor (ε″) of barley at 23°C and indicated moisture contents and bulk densities.

Frequency (GHz)	Dielectric Properties	Moisture Content (M, %) and Bulk Density (ρ, g cm^{-3})					
		M = 10.8, ρ = 0.686	M = 13.0, ρ = 0.660	M = 15.8, ρ = 0.661	M = 17.6, ρ = 0.650	M = 20.8, ρ = 0.588	M = 24.8, ρ = 0.567
5	ε′	2.23	2.28	2.47	2.53	2.63	2.82
	ε″	0.15	0.19	0.27	0.32	0.41	0.47
6	ε′	2.21	2.26	2.44	2.49	2.58	2.76
	ε″	0.16	0.20	0.28	0.32	0.42	0.49
7	ε′	2.20	2.24	2.41	2.47	2.54	2.72
	ε″	0.16	0.20	0.29	0.33	0.43	0.51
8	ε′	2.19	2.23	2.38	2.44	2.52	2.68
	ε″	0.17	0.21	0.30	0.34	0.44	0.53
9	ε′	2.17	2.20	2.35	2.41	2.48	2.64
	ε″	0.18	0.21	0.30	0.34	0.45	0.55
10	ε′	2.15	2.18	2.33	2.37	2.45	2.59
	ε″	0.17	0.21	0.30	0.34	0.46	0.57
11	ε′	2.14	2.17	2.31	2.35	2.42	2.55
	ε″	0.17	0.20	0.30	0.33	0.47	0.57
12	ε′	2.14	2.17	2.31	2.35	2.40	2.52
	ε″	0.16	0.20	0.29	0.33	0.47	0.58
13	ε′	2.14	2.17	2.31	2.34	2.37	2.49
	ε″	0.16	0.20	0.29	0.34	0.47	0.58
14	ε′	2.14	2.17	2.31	2.34	2.35	2.46
	ε″	0.16	0.20	0.29	0.35	0.47	0.59
15	ε′	2.13	2.17	2.29	2.34	2.34	2.44
	ε″	0.17	0.21	0.29	0.36	0.48	0.61

Table 4. Dielectric constant (ε′) and loss factor (ε″) of oats at 23°C and indicated moisture contents and bulk densities.

Frequency (GHz)	Dielectric Properties	Moisture Content (M, %) and Bulk Density (ρ, g cm^{-3}) M = 9.1, ρ = 0.479	M = 11.0, ρ = 0.467	M = 13.3, ρ = 0.479	M = 15.1, ρ = 0.469	M = 17.5, ρ = 0.456	M = 18.3, ρ = 0.456
5	ε′	1.71	1.77	1.87	1.95	2.02	2.04
	ε″	0.07	0.09	0.14	0.17	0.19	0.21
6	ε′	1.70	1.76	1.85	1.93	1.99	2.00
	ε″	0.06	0.10	0.15	0.17	0.20	0.22
7	ε′	1.69	1.75	1.83	1.91	1.97	1.97
	ε″	0.06	0.10	0.15	0.17	0.21	0.22
8	ε′	1.69	1.74	1.81	1.90	1.95	1.96
	ε″	0.07	0.10	0.16	0.18	0.22	0.23
9	ε′	1.69	1.73	1.79	1.88	1.93	1.93
	ε″	0.07	0.10	0.16	0.18	0.22	0.23
10	ε′	1.68	1.72	1.78	1.87	1.91	1.91
	ε″	0.08	0.10	0.15	0.18	0.22	0.24
11	ε′	1.67	1.72	1.77	1.86	1.89	1.89
	ε″	0.07	0.11	0.15	0.18	0.22	0.23
12	ε′	1.67	1.72	1.77	1.85	1.88	1.88
	ε″	0.07	0.11	0.15	0.18	0.22	0.23
13	ε′	1.68	1.71	1.77	1.85	1.88	1.87
	ε″	0.07	0.10	0.15	0.18	0.21	0.22
14	ε′	1.68	1.71	1.77	1.85	1.87	1.87
	ε″	0.07	0.10	0.15	0.18	0.22	0.23
15	ε′	1.68	1.71	1.77	1.85	1.87	1.86
	ε″	0.08	0.10	0.15	0.18	0.22	0.23

attenuation of at least 10 dB to avoid multiple reflections and that did not exceed the dynamic range of the VNA. For each sample of given moisture content, measurements were carried out at bulk densities close to those corresponding to normal test weights for these cereal grains. The sample bulk density was calculated by dividing the sample weight by the inside volume of the Styrofoam container.

After the microwave measurements were completed, moisture content of each sample was determined according to standard procedures (*ASAE Standards*, 2000). The moisture content (M) in percent, wet basis, is defined as:

$$M = \frac{m_w}{m_w + m_d} \times 100 \quad (3)$$

where m_w is the mass of water, and m_d is the mass of dry matter.

All of the physical characteristics, i.e., bulk density, moisture content, and temperature of each sample were assumed to be the same throughout the entire volume of the sample.

Table 5. Dielectric constant (ε′) and loss factor (ε″) of grain sorghum at 23°C and indicated moisture contents and bulk densities.

Frequency (GHz)	Dielectric Properties	Moisture Content (M, %) and Bulk Density (ρ, g cm^{-3}) M = 10.1, ρ = 0.776	M = 10.87, ρ = 0.769	M = 13.4, ρ = 0.760	M = 15.9, ρ = 0.778	M = 18.2, ρ = 0.760	M = 20.2, ρ = 0.767	M = 23.1, ρ = 0.746	M = 25.3, ρ = 0.747
5	ε′	2.48	2.52	2.73	3.02	3.25	3.59	3.92	4.21
	ε″	0.21	0.23	0.34	0.45	0.57	0.69	0.80	0.88
6	ε′	2.45	2.49	2.68	2.95	3.17	3.47	3.79	4.08
	ε″	0.21	0.23	0.34	0.45	0.57	0.72	0.85	0.95
7	ε′	2.42	2.47	2.65	2.90	3.10	3.37	3.68	3.95
	ε″	0.21	0.22	0.34	0.45	0.58	0.71	0.86	0.97
8	ε′	2.41	2.46	2.63	2.86	3.06	3.31	3.60	3.86
	ε″	0.20	0.22	0.33	0.46	0.60	0.70	0.87	0.99
9	ε′	2.40	2.44	2.60	2.83	3.02	3.26	3.52	3.76
	ε″	0.20	0.22	0.33	0.46	0.61	0.69	0.87	1.01
10	ε′	2.38	2.43	2.59	2.80	2.99	3.21	3.45	3.66
	ε″	0.20	0.22	0.32	0.46	0.61	0.69	0.87	1.03
11	ε′	2.37	2.41	2.56	2.77	2.96	3.17	3.39	3.57
	ε″	0.19	0.22	0.31	0.46	0.62	0.68	0.86	1.04
12	ε′	2.37	2.41	2.55	2.76	2.95	3.14	3.35	3.52
	ε″	0.19	0.22	0.30	0.46	0.62	0.67	0.85	1.03
13	ε′	2.37	2.40	2.53	2.74	2.93	3.11	3.32	3.45
	ε″	0.19	0.21	0.30	0.46	0.61	0.67	0.85	1.03
14	ε′	2.36	2.40	2.52	2.73	2.92	3.09	3.29	3.47
	ε″	0.19	0.21	0.30	0.45	0.60	0.67	0.86	1.05
15	ε′	2.36	2.40	2.52	2.73	2.91	3.07	3.26	3.45
	ε″	0.19	0.20	0.30	0.45	0.59	0.68	0.87	1.09

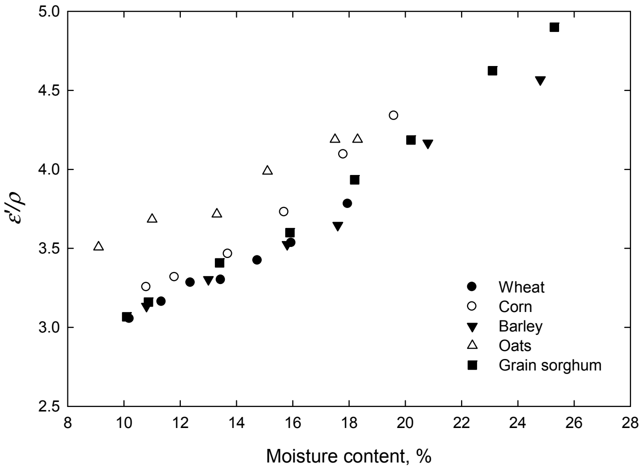

Figure 3. Variation of dielectric constant, divided by density, with moisture content for indicated cereal grains at 10 GHz and 23°C.

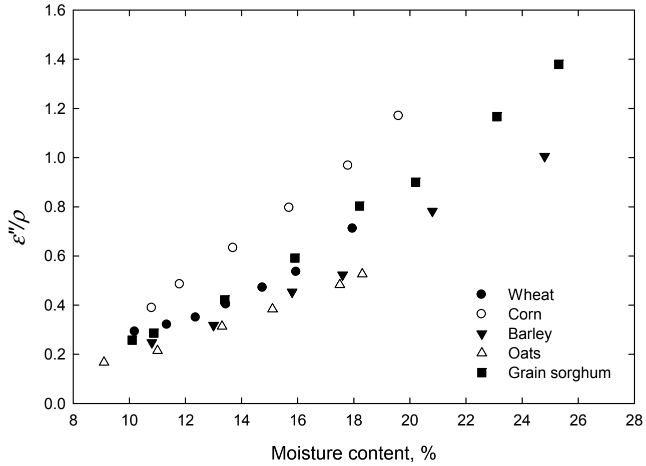

Figure 4. Variation of dielectric loss factor, divided by density, with moisture content for indicated cereal grains at 10 GHz and 23°C.

RESULTS

Relationships between bulk density of the five cereal grain lots and moisture content are illustrated in figure 2. The bulk density decreases nearly linearly with moisture content, which is very similar to the behavior noted previously for wheat and corn (Nelson, 1980; Nelson and Stetson, 1976).

From all the microwave dielectric properties data collected, only those corresponding to samples providing attenuation between 10 and 35 dB are reported. This criterion was used to eliminate measurements that were affected either by multiple reflections or reaching the noise level of the VNA. Resulting values for the dielectric constant and loss factor of each of the five cereal grains are shown for each frequency and each moisture level in tables 1 to 5, where the corresponding bulk densities are also listed. In some instances, the dielectric properties may be needed for bulk densities different from those presented in this article. The Landau and Lifshitz, Looyenga mixture equation (Nelson, 1984) can be used to calculate the relative complex permittivity at bulk densities different from those tabulated in this article:

$$\varepsilon_2 = \left[\left(\varepsilon_1^{1/3} - 1\right)\frac{\rho_2}{\rho_1} + 1\right]^3 \qquad (4)$$

where ε_1 and ρ_1 are the known relative complex permittivity and bulk density, respectively, and ε_2 is the relative complex permittivity to be determined for the same material (same moisture content) at a different bulk density ρ_2. Equation 4 was selected from several dielectric mixture equations that were tested to find the one with best performance for dielectric properties similar to those of cereal grains (Nelson, 1992).

DISCUSSION

In the tabulations of dielectric properties (tables 1 to 5), the dielectric constant consistently increases with increasing grain moisture content and decreases gradually with increasing frequency. The dielectric loss factor tends to increase with increasing moisture content at all frequencies. The loss factor shows little variation with frequency at lower moisture contents; however, it shows a tendency to

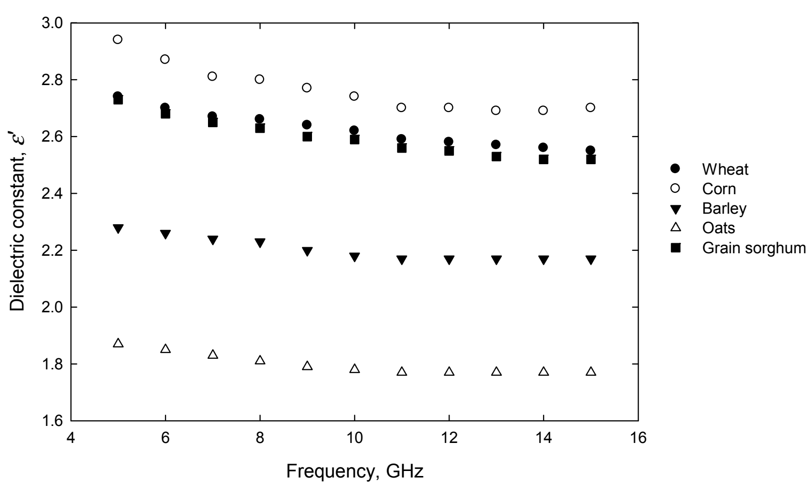

Figure 5. Variation of the dielectric constant with frequency at 23°C for wheat (*M* = 13.45%, ρ = 0.794 g cm^{-3}), corn (*M* = 13.7%, ρ = 0.791 g cm^{-3}), barley (*M* = 13.0%, ρ = 0.660 g cm^{-3}), oats (*M* = 13.3%, ρ = 0.479 g cm^{-3}), and grain sorghum (*M* = 13.4%, ρ = 0.70 g cm^{-3}).

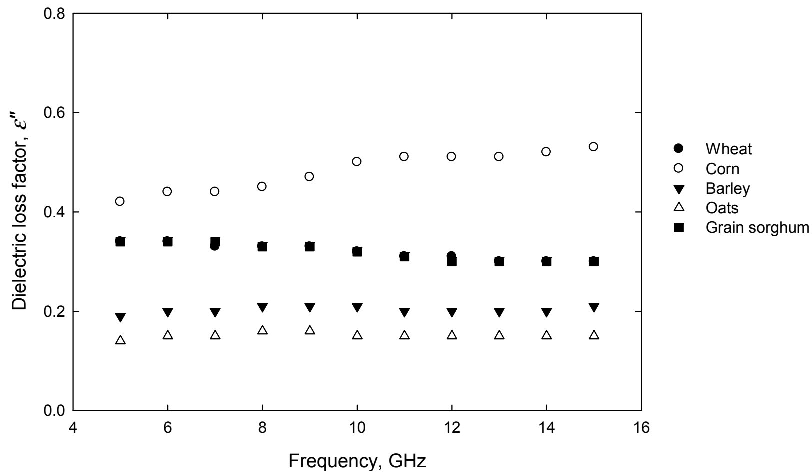

Figure 6. Variation of the dielectric loss factor with frequency at 23°C for wheat (M = 13.45%, ρ = 0.794 g cm^{-3}), corn (M = 13.7%, ρ = 0.791 g cm^{-3}), barley (M = 13.0%, ρ = 0.660 g cm^{-3}), oats (M = 13.3%, ρ = 0.479 g cm^{-3}), and grain sorghum (M = 13.4%, ρ = 0.70 g cm^{-3}).

increase with increasing frequency at higher moisture levels. For purpose of illustration, variations of the dielectric properties divided by bulk density as a function of moisture content are presented in figures 3 and 4 at a mid-band frequency of 10 GHz. Bulk density influences the dielectric properties, so division of those properties by bulk density removes most of that effect. Both the dielectric constants and dielectric loss factors, divided by bulk density, increase nearly linearly with moisture content. The same trends were observed at the other frequencies. Such behavior constitutes the basis for the use of dielectric properties in grain moisture sensing applications (Kent and Kress-Rogers, 1986; Kraszewski and Kulinski, 1976; Meyer and Schilz, 1980; Trabelsi et al., 1998b). Figures 5 and 6 show variations of the dielectric constant and dielectric loss factor with frequency for similar moisture levels and indicated bulk densities for all five grains. As expected, the dielectric constant decreases with frequency. The dielectric loss factor remains nearly constant for barley and oats and decreases with increasing frequency for wheat and grain sorghum. However, the dielectric loss factor of corn shows a slight increase with increasing frequency, which might be related to some scattering effect, given the geometry and size of the corn kernels that is not accounted for in the attenuation measurements.

CONCLUSIONS

Dielectric properties of five cereal grains (wheat, corn, barley, oats, and grain sorghum) were measured at 23°C with a free-space transmission technique between 5 and 15 GHz for moisture contents of interest to the grain industry and at bulk densities that are close to the corresponding test weight. The dielectric constants of all grain lots decreased with increasing frequency and increased with increasing moisture content. Dielectric loss factors also generally increased with increasing moisture content. Loss factors varied little with increasing frequency, remaining nearly constant for barley and oats, decreasing slightly with increasing frequency for wheat and grain sorghum, and increasing slightly with increasing frequency for corn. The data collected are useful in developing moisture sensing equipment and for considering microwave dielectric heating applications for cereal grains.

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