Review of Factors Influencing the Dielectric Properties of Cereal Grains[1]

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ABSTRACT

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The influence of various factors such as frequency, moisture content, grain density, temperature, chemical composition, and sorption-desorption cycles on the dielectric properties of grain are discussed, based on information in the literature. Frequency and moisture content are the two most important factors. Bulk density and temperature also influence the values of the dielectric properties. The dielectric constant decreases with increasing frequency and decreasing moisture content. It exhibits positive bulk-density and temperature coefficients, whereas the loss tangent and the dielectric loss factor have positive density coefficients but may have positive or negative temperature coefficients, depending upon frequency, moisture-content, and temperature ranges. Dielectric properties of wheat and corn are presented as contour plots for the dielectric constant and the dielectric loss factor as functions of moisture content and frequency. Equations expressing the dielectric constant of shelled, yellow-dent field corn as a function of frequency, moisture content, bulk density, and temperature are also given. Sources of information on dielectric properties of cereal grains are identified in a table indicating ranges of moisture content, frequency, and temperature for which information is available.

The electrical properties of cereal grains have been of interest mainly because of their usefulness in providing quick estimates of grain moisture content. Over the past 50 years, numerous instruments have been developed for measuring grain moisture content by electrical means (Nelson 1977). Electrical moisture testers are well established in the grain trade because they are relatively inexpensive and yet provide the rapid test results needed in commerce with a generally acceptable degree of reliability.

The reliability of dc or low-frequency moisture meters that measure electrical conductivity became questionable when grain drying came into practice, because their measurements were dependent upon the distribution of moisture within the kernel. Instruments that sensed the dielectric properties then became more popular because dry outer layers of the kernels did not degrade their reliability as much. The reliability of the dielectric type of grain-moisture meter, however, also deteriorates at grain moisture levels above about 25%, and this has caused concern because much grain, especially corn, is harvested at high moisture levels.

Although the dielectric properties of grain were used for grain moisture measurement, knowledge of the actual values for these properties was not absolutely necessary, because most work involved the response of particular instruments to grain of different moisture levels and calibration against approved oven moisture-determination methods. Other potential applications brought about the need for information on the actual values of the dielectric properties (Nelson et al 1953). Knowledge about the values of the dielectric properties of grain was important in research on radiofrequency dielectric heating of grain to control insects in stored grain. In this instance, the relative dielectric properties of the insects and the grain were needed for assessment of the degree of selective dielectric heating that might be achieved (Nelson and Charity 1972, Nelson and Whitney 1960). The dielectric properties of grain were also studied in connection with radiofrequency dielectric heating for grain drying (Knipper 1959).

Another application that involves electrical moisture content measurement is the monitoring of the moisture content of flowing grain or grain milling products for process control. The dielectric properties of the materials have been studied for such use in grain drying (Ban and Suzuki 1977) and in milling (Kraszewski et al 1977, Mládek and Milácek 1975).

DIELECTRIC PROPERTIES

The dielectric properties usually of interest are the dielectric constant and dielectric loss factor, the real and imaginary parts, respectively, of the complex relative permittivity, $\epsilon_r^* = \epsilon_r' - j\epsilon_r''$, the loss tangent, $\tan \delta = \epsilon_r''/\epsilon_r'$, and the electrical conductivity, $\sigma = \omega\epsilon_0\epsilon_r''$, where $\omega = 2\pi f$ is the angular frequency, and ϵ_0 is the permittivity of free space. These quantities have been defined and discussed in detail elsewhere from the point of view of both electrical circuit concepts (Nelson 1965) and electromagnetic field concepts (Nelson 1973a). Basically, the dielectric constant, ϵ_r', of a material is related to its capability for storing energy in an electric field in the material, whereas the loss factor, ϵ_r'', is related to the capability of the material for absorbing energy from the electric field. These properties depend not only upon the chemical composition of materials, but also upon their temperature and the frequency of the applied alternating electric field. Explanations of various dielectric relaxation mechanisms that account for the frequency and temperature dependence of dielectric properties are complicated, and the processes are not entirely understood (Daniel 1967, Hill et al 1969, Nelson 1973a). Several studies have revealed information on the dielectric behavior of cereal grains, however, and this information is summarized here.

DIELECTRIC PROPERTIES OF GRAIN

Dependence on Frequency and Moisture Content

Early measurements of the dielectric properties of wheat, corn, oats, and barley over the frequency range from 1 to 50 MHz revealed that ϵ_r' increased with grain moisture content at any given frequency, and that, for a given moisture content, ϵ_r' either decreased or remained constant with increasing frequency (Nelson 1952, Nelson et al 1953). Measurements on wheat and other kinds of grain and seed over the frequency ranges from 50 kHz to 30 MHz (Knipper 1959) and from 1 to 50 MHz (Nelson 1965) confirmed these general observations and indicated that ϵ_r'' and $\tan \delta$ might either increase or decrease with frequency, depending upon the frequency range and moisture content.

Similar relationships were observed in studies that extended information on dielectric properties to both lower and higher frequencies. Data obtained on the dielectric properties of several kinds of grain and seed at various moisture contents in the 250-Hz to 20-kHz frequency range revealed considerably higher ϵ_r' values than were found at radiofrequencies (Stetson and Nelson 1972). At any given frequency, ϵ_r' was positively correlated with moisture content, but $\tan \delta$ and ϵ_r'' increased with moisture content in some instances and decreased in others, depending upon the frequency and moisture-content ranges. An interesting relaxation phenomenon was noted in the audiofrequency range, with relaxation frequencies regularly dependent upon moisture content.

At microwave frequencies between 1 and 5.5 GHz, both ϵ_r' and ϵ_r'' for hard red winter wheat increased regularly with increasing moisture content, and ϵ_r' decreased as frequency increased (Nelson 1973b). The loss factor exhibited relatively little dependence upon frequency but tended to increase with frequency at the higher end of

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the moisture-content range studied (6–21%). Similar relationships were reported for hard red spring wheat at frequencies of 2.45 and 9.4 GHz (Chugh et al 1973).

Data on the dependence of the dielectric properties of grain on frequency and moisture content have been obtained over very wide frequency ranges (from 250 Hz to 12 GHz) for wheat and a few other grains and seeds (Nelson and Charity 1972; Nelson and Stetson 1975,1976). Shapes of curves of ϵ_r' vs moisture content and ϵ_r'' vs moisture content for wheat of 3–24% moisture content varied considerably over this wide frequency range (Nelson and Stetson 1976). Behavior of ϵ_r' was regular in that it decreased with increasing frequency and decreasing moisture content. The behavior of tan δ and ϵ_r'' was irregular, most likely because of dielectric relaxation and dispersion phenomena. Similar statements are applicable to findings from other studies on corn over the range from 1 MHz to 11 GHz with moisture contents ranging from 10 to 50% (Nelson 1978a,1979b) and to those from studies on wheat, corn, and soybeans over the frequency range from 1 to 200 MHz (Jones et al 1978).

Dependence on Density

In addition to frequency and moisture content, the density of grain influences the dielectric properties. Both ϵ_r' and ϵ_r'' of oats at frequencies between 1 and 20 kHz increased linearly with moisture content over a bulk-density range achieved by loosely filling and settling the oats samples in the sample holder (Stetson and Nelson 1972). However, when a much greater range of bulk densities was used for 9.4-GHz measurements on hard red winter wheat, the relationships between density and ϵ_r' or ϵ_r'' deviated somewhat from linearity and were well described by quadratic equations (Nelson 1976). For observation of the nonlinearity, the wheat samples had to be compressed with such force that the kernels were crushed and broken. Over natural and narrower ranges of bulk density on field corn samples, relationships between ϵ_r' and bulk density (ρ_b) appeared linear at moisture contents between 10 and 35% (Nelson 1978b,1979b). Slopes of the ϵ_r'-vs-ρ_b lines increased as moisture content increased, indicating that the dependence of ϵ_r' on ρ_b was enhanced by moisture. The range of natural densities encountered also increased as grain moisture content increased.

The large variation in ϵ_r' at high moisture content, because of ρ_b variation, was also noted in a study on corn, wheat, and soybeans, in which dielectric properties of whole samples dropped into sample holders were compared with the dielectric properties of the same samples after they were settled (Jones et al 1978). Ratios of ϵ_r' of the settled samples to ϵ_r' of the nonsettled samples at 1 MHz increased at a faster rate than did bulk-density ratios as moisture content increased. Tan δ ratios at this frequency appeared to follow the bulk-density ratios reasonably well over the range of moisture contents studied. Settling the samples increased the ϵ_r'' values more than it did the ϵ_r' values, which prompted the observation that ϵ_r'' might be useful in correcting ϵ_r' for density variations in moisture-content measurement. Correction for ρ_b on the basis of measuring both attenuation and phase shift at microwave frequencies has been suggested (Kraszewski et al 1977).

Several aspects of the dependence of dielectric properties on grain density can be considered. One deals with the variation in ρ_b of any given sample, and this has received some attention, as already noted. Another deals with the variation in ρ_b among different lots of the same kind of grain. This aspect is much more difficult to study because variations in physical characteristics such as kernel shape and size and differences in chemical composition can contribute to variation in the dielectric properties as well as can the variations in ρ_b or test weight. Variation in kernel density also exists. Then, too, both ρ_b and kernel density are highly dependent upon moisture content (Nelson 1980). However, kernel density and ρ_b are well correlated over reasonably wide moisture content ranges (Nelson 1980).

Dependence on Temperature

Data from some of the early studies indicated that ϵ_r' and ϵ_r'' varied linearly with temperature at 40 MHz (Nelson 1965), and that, at frequencies between 54 kHz and 9.6 MHz, ϵ_r'' was linearly related to temperature (Knipper 1959). Although ϵ_r' was positively correlated with temperature, ϵ_r'' could either increase or decrease with temperature, depending upon frequency and moisture content.

In more recent work on microwave dielectric properties of hard red spring wheat, temperature dependence of ϵ_r' and ϵ_r'' for moisture contents from 0.5 to 25% was reported for temperatures from −20 to 80°C (Chugh et al 1973). Positive temperature coefficients were obtained for ϵ_r' at 2.45 and 9.4 GHz and for ϵ_r'' at 9.4 GHz, but both positive and negative temperature coefficients were observed for ϵ_r'' at 2.45 GHz, depending upon temperature range and moisture content. Positive temperature coefficients for ϵ_r' at 30 MHz were also reported for wheat, corn, and soybeans at a few moisture contents over temperature ranges bounded by 2 and 40°C (Jones et al 1978). Both positive and relatively small negative temperature coefficients were reported for tan δ of wheat, depending upon moisture content and temperature range, whereas temperature coefficients for tan δ of corn and soybeans were positive in the limited moisture ranges studied. Positive temperature coefficients for ϵ_r' were also obtained for corn of about 10 and 19% moisture at frequencies of 20 and 300 MHz and 2.45 GHz over the temperature range from 25 to 60°C (Nelson 1979b).

Other Factors

A few additional factors should be noted that may influence the dielectric properties determined for grain. First, because grains are nonhomogeneous materials and calculations involved in the measurement of dielectric properties are generally based upon homogeneous dielectrics, the effective dielectric properties of the granular materials can differ as a result of different spacings between the electrodes of the sample holder. This phenomenon has been observed in at least two independent studies (Jones et al 1978, Nelson 1979a). When kernel dimensions and, consequently, dimensions of the interstitial air spaces are appreciable fractions of the interelectrode spacing, the nonhomogeneity of the dielectric apparently comes into play. When this effect becomes significant, the ϵ_r' determined with closer electrode spacing is smaller than that obtained with greater electrode spacing (Jones et al 1978, Nelson 1979a). Small differences because of this effect were also reported for tan δ (Jones et al 1978). The particulate nature of the dielectric can also introduce problems at microwave frequencies at which wavelengths in the materials may not be long with respect to kernel dimensions.

An "overburden effect" has been suggested as another factor that may affect the dielectric properties of grain (Jones et al 1978). However, examination of the data indicates that the increase in the measured value of ϵ_r' may have resulted simply because of an increase in ρ_b. Changes of 2.7 and 3.5% in sample length translate into sample density changes of 2.7 and 3.5%, respectively, whereas, corresponding changes in ϵ_r' were 0.3 and 1.2%. Thus, the increase in ρ_b as a result of compression could very well account for the increases observed in ϵ_r'.

Questions have also been raised as to whether the dielectric properties of grain at high moisture contents at harvest time are different from those of the same grain to which moisture has been added, after drying, to bring it back to the original moisture level. In general, the question is whether the dielectric properties change as a result of sorption-desorption cycles. Because kernel densities, as well as kernel volumes and weights, exhibit a hysteresis in the sorption and desorption of moisture (Bushuk and Hlynka 1960), one might expect the dielectric properties to be affected somewhat through the influence of ρ_b if for no other reason. Few comparison measurements of dielectric properties dealing with this question have been reported. In the frequency range from 1 to 50 MHz, differences between dielectric properties of the grain at 12% moisture content after harvest and when rewetted after drying were less than 5% (Soderholm 1953). In other tests, differences between naturally dried and tempered wheat were well within the range of variation noted among seven cultivars of hard red winter wheat (Nelson and Stetson 1976). In these comparisons, the ϵ_r' of wheat tempered by the addition of water was slightly lower than that of wheat drying naturally after harvest. In another comparison, the audiofrequency dielectric properties of hard red winter wheat were very nearly the same for sorption and desorption in the moisture-content range from 6.6 to 19.5% (Stetson and Nelson 1972).

Most of the data obtained on dielectric properties of grain were from measurements taken on clean samples of sound grain. The presence of foreign matter, insect infestation, or particles of broken kernels will obviously influence the dielectric properties. Any spoilage in high-moisture grain could also be expected to affect the dielectric properties. The effects of spoilage would probably be more noticeable at low frequencies, at which the contribution of ionic conduction can be greater than it is at high frequencies.

Whether dielectric properties are influenced by chemical compositon other than moisture content has not been studied extensively. However, no correlation was observed between dielectric properties and protein, fat, or ash content of several hard red winter wheat lots (Nelson and Stetson 1976). If differences due to composition existed, they were masked by variability resulting from other factors.

Finally, the methods of moisture-content measurement should be kept in mind when comparing data on dielectric properties from different laboratories. Most reported work has been based on some method of oven moisture determination. Generally, such methods are described or some accepted method is cited, but appreciable differences in oven moisture-content determinations can result depending upon the techniques employed (Hunt and Neustadt 1966; Matthews 1962; Nelson 1978b,1979b). Also, moisture contents for grain are usually stated on the wet basis, but such data can be reported on the basis of dry weight; these must not be confused.

General Variability

That variation exists in the dielectric properties of the same kind of grain from different sources and grown in different seasons is well known. The difficult question to answer is to what extent variation in data from the literature can be accounted for by differences in measurement techniques and reliability. Enough information is available to make reasonably good corrections for moisture content, temperature, and even frequency variations for some kinds of grain. Attempts can be made to adjust values for bulk density, but assessment of the inherent variability of the dielectric properties of a particular kind of grain is very risky when based on data obtained by different methods in different laboratories. Perhaps useful information on inherent variability of dielectric properties could be derived from records and data obtained in standardization laboratories where calibration testing of particular electronic grain-moisture meters has been carried out under carefully controlled and consistent procedures with numerous grain samples from various sources over several years.

Some data on the variability of the dielectric properties of grain have been obtained over relatively small numbers of samples. Ranges of variation in ϵ_r' and ϵ_r'' observed in seven cultivars of hard red winter wheat at 10 kHz, 5.1 and 100 MHz, and 5.5 GHz have been presented graphically over a moisture-content range from 3 to 24% (Nelson and Stetson 1976). In general, ϵ_r' exhibited less variation than did ϵ_r'', and the amount of variation increased with moisture content, especially at the low frequencies. Coefficients of variation (standard deviation divided by the sample mean) for the dielectric properties of 21 lots of shelled, hybrid, yellow-dent field corn over the 10–35% moisture range were about 3 or 4% for ϵ_r' and about twice that large for ϵ_r'' at frequencies of 20 and 300 MHz and 2.45 GHz (Nelson 1979b). Thus, ϵ_r' was the better indicator of moisture content, and its variability was about the same at all three frequencies.

Dielectric properties can vary considerably among different types from the same species. Dielectric constants of flint and floury-endosperm types of corn differed by 5–18% from those of averages for yellow-dent field corn in work at 20 and 300 MHz and 2.45 GHz over moisture content ranges from 10 to 35% (Nelson 1978b). Flint types had larger dielectric constants, whereas, the floury-endosperm type had smaller dielectric constants.

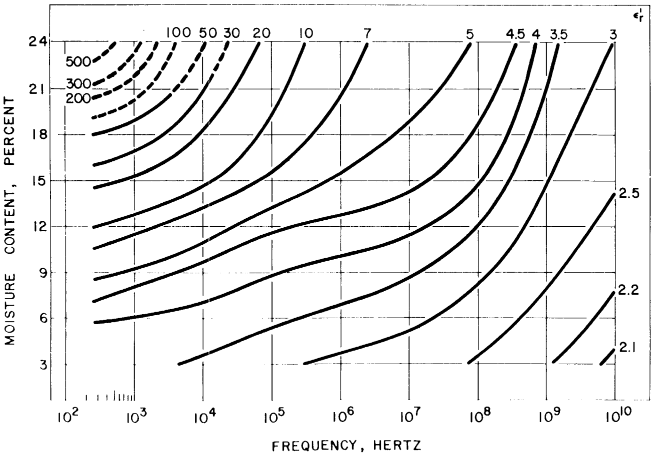

Fig. 1. Contour plots of the dielectric constant (ϵ_r') of hard red winter wheat, *Triticum aestivum* L., at 24°C as a function of frequency and wet-basis moisture content. Averages are for seven lots of sound, clean wheat. Dashed curves indicate region where values may have been influenced by electrode polarization. Condensed from data in Nelson and Stetson (1976).

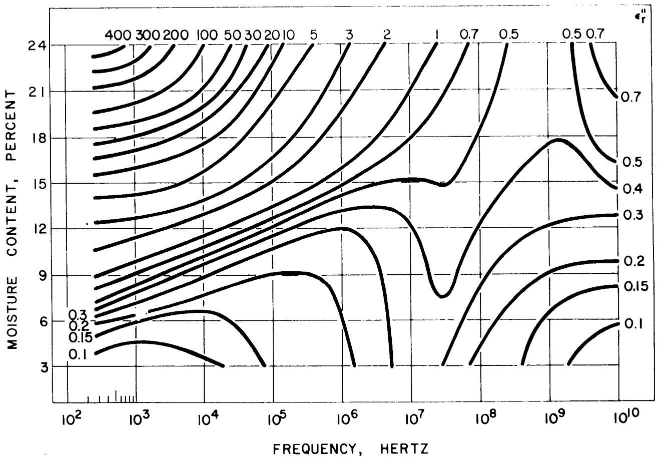

Fig. 2. Contour plots of the dielectric loss factor (ϵ_r'') of hard red winter wheat, *Triticum aestivum* L., at 24°C as a function of frequency and wet-basis moisture content. Averages are for seven lots of sound, clean wheat. Condensed from data in Nelson and Stetson (1976).

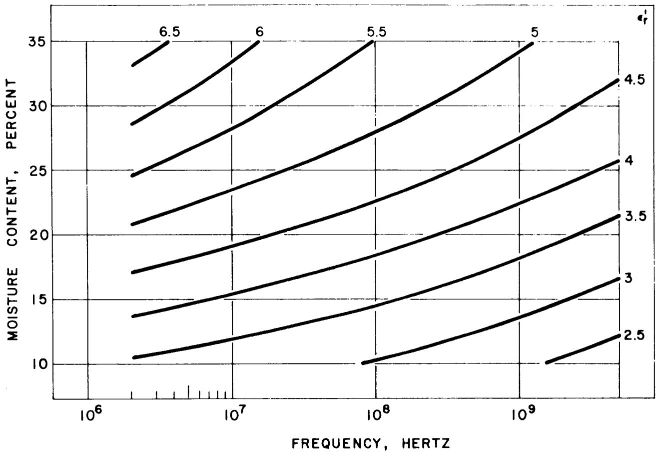

Fig. 3. Contour plots of the dielectric constant (ϵ_r') of shelled, hybrid, yellow-dent field corn, *Zea mays* L., at 24°C as a function of frequency and wet-basis moisture content. Averages are for 21 lots of sound, clean corn. Condensed from data in Nelson (1979b).

Dielectric Property Values

Because the data on the dielectric properties of hard red winter wheat (Nelson and Stetson 1976) and shelled, hybrid, yellow-dent field corn (Nelson 1979b) are the most comprehensive available with respect to range of frequency and moisture content, and because they are representative of several lots, contour plots summarizing these data are presented in Figs. 1–3. Unfortunately, data on ϵ_r'' were not available at a sufficient number of frequencies to determine the ϵ_r'' contours for corn. These graphs provide quick estimates for the dielectric properties of these kinds of grain at 24° C

TABLE I
Sources of Information on Dielectric Properties of Grain and Related Crops

Material	Frequency	Moisture Content (%)	Temperature (°C)	Other Factors Studied	Reference
Wheat	250 Hz to 20 kHz	10–15.8	24	···	Stetson and Nelson (1972)
	250 Hz to 12 GHz	10.6, 12.5	24	···	Nelson and Charity (1972), Nelson and Stetson (1975)
	250 Hz to 12 GHz	2.7–23.8	24	Variability	Nelson and Stetson (1976)
	1 kHz to 9.5 GHz	12, 17	···	···	Kormakov et al (1978)
	50 kHz to 30 MHz	2.3–28.4	17–53	···	Knipper (1959)
	50 kHz to 50 MHz	10.6	24	···	Nelson (1965)
	100 kHz to 10 MHz	8.3–24.5	27	···	Ban and Suzuki (1977)
	1–50 MHz	7.2–19.3	24	···	Nelson (1965)
	1–200 MHz	10–22	23	Density, electrode spacing	Jones et al (1978)
	5 MHz	20	20–50	···	Torosyan and Konokhova (1972)
	10, 40 MHz	12.8–23.5	22	Electrode spacing	Nelson (1979a)
	30 MHz	13–21	3–40	···	Jones et al (1978)
	30 MHz to 1 GHz	11.7	25	···	Kwok et al (1979)
	1–5.5 GHz	5.5–21	24	···	Nelson (1973)
	1–12.1 GHz	12.5	24	···	Nelson (1973)
	9.3 GHz	3–25	25	···	Mládek and Milácek (1975)
	9.4 GHz	11–18	25	···	Kraszewski et al (1977) Kraszewski (1978)
	9.4 GHZ	11.5–17.8	24	Density	Nelson (1976)
Corn	250 Hz to 20 kHz	8.8–14.2	24	···	Stetson and Nelson (1972)
	1–11 MHz	10–50	24	Variability	Nelson (1978a)
	1, 30 MHz	35	7–22	···	Jones et al (1978)
	1–50 MHz	8.1–20.3	24	···	Nelson (1965)
	1–200 MHz	17–34	23	Density, electrode spacing	Jones et al (1978)
	5 MHz	20	20–50	···	Torosyan and Konokhova (1972)
	20,300 MHz, 2.45 GHz	10–35	24–60	Density, variability	Nelson (1979b)
	20,300 MHz, 2.45 GHz	10–35	24–60	Type, density, variability	Nelson (1978b)
Soybean	250 Hz to 20 kHz	6.1–12.7	24	···	Stetson and Nelson (1972)
	250 Hz to 12 GHz	8.5	24	···	Nelson and Stetson (1975)
	1–50 MHz	4.6–11.5	24	···	Nelson (1965)
	1–200 MHz	10–17	23	Density, electrode spacing	Jones et al (1978)
	30 MHz	10.4–16.1	2–40	···	Jones et al (1978)
	1–12.1 GHz	8.5	24	···	Nelson (1973)
Oats	250 Hz to 20 kHz	7.7–14	24	Density	Stetson and Nelson (1972)
	250 Hz to 12 GHz	10.7	24	···	Nelson and Stetson (1975)
	50 kHz to 30 MHz	13–18.5	19–22	···	Knipper (1959)
	1–50 MHz	6.8–25.8	24	···	Nelson (1965)
	1–12.1 GHz	10.7	24	···	Nelson (1973)
Barley	50 kHz to 30 MHz	13.6, 17	18–20	···	Knipper (1959)
	100 kHz to 10 MHz	6.9–27	27	···	Ban and Suzuki (1977)
	1–50 MHz	12.6	~27	···	Nelson (1953)
	1–50 MHz	8.8–20	24	···	Nelson (1965)
Grain sorghum	250 Hz to 20 kHz	6.8–15.1	24	···	Stetson and Nelson (1972)
	250 Hz to 12 GHz	11.4	24	···	Nelson and Stetson (1975)
	1–50 MHz	10.4–19.9	24	···	Nelson (1965)
Rice	100 kHz to 3 MHz	3.5–11.6	···	···	Katur and Gupta (1973)
	100 kHz to 10 MHz	13.3–19.8	11.5–34	Moisture distribution	Ban and Suzuki (1977)
	27 MHz	10–21.1	24	···	ASAE (1966)
Rye	50 kHz to 30 MHz	13.6–17.6	18, 21	···	Knipper (1959)
	40 MHz	12.7	24	···	Nelson (1965)
Pea	50 kHz to 30 MHz	15.5	20	···	Knipper (1959)
	5 MHz	20	20–50	···	Torosyan and Konokhova (1972)
Buckwheat	5 MHz	20	20–50	···	Torosyan and Konokhova (1972)
Field bean	10, 40 MHz	8.7	24	···	Nelson (1965)
Millet	10, 40 MHz	9.8, 11.4	24	···	Nelson (1965)

at any given frequency and moisture content within the range of the data. Equations that permit calculation of ϵ_r' for shelled, hybrid, yellow-dent field corn were also developed in the same study (Nelson 1979b). These equations for ϵ_r' as a function of moisture content (M, in percent, wet basis), ρ_b, (in grams per cubic centimeter), and temperature (T, in degrees Celsius) at frequencies of 20, 300, and 2,450 MHz are as follows:

$$\epsilon'_{r20} = 3.51 + 0.132(M - 10) + (\rho_b - \overline{\rho_b})(0.839 - 0.086M + 0.027M^2) + 0.012\,(T - 24) \tag{1}$$

$$\epsilon'_{r300} = 2.89 + 0.098(M - 10) + (\rho_b - \overline{\rho_b})(0.460M - 2.16) + 0.015\,(T - 24) \tag{2}$$

$$\epsilon'_{r\,2,450} = 2.48 + 0.099(M - 10) + (\rho_b - \overline{\rho_b})(0.387M - 3.22) + 0.013\,(T - 24). \tag{3}$$

The required value for $\overline{\rho_b}$, the mean bulk density of such corn lots, can be obtained from a curve (Nelson 1979b) or calculated from the following equation:

$$\overline{\rho_b} = 0.6829 + 0.01422M - 0.000979M^2 + 0.0000153M^3. \tag{4}$$

Although equations were not developed for ϵ_r'', and an ϵ_r'' companion contour plot could not be drawn for Fig. 3, values for ϵ_r'' were presented graphically for 20, 300, and 2,450 MHz (Nelson 1979b).

Another approach, involving dielectric mixture theory, has been used successfully to calculate the dielectric properties of wheat at 9.4 GHz (Kraszewski 1978). When bulk wheat was modeled as a mixture of air inclusions in a medium with the dielectric properties of wheat kernels at specific moisture contents (Nelson 1976), values calculated for ϵ_r' and ϵ_r'' of the mixture agreed well with measured values (Kraszewski 1978). Little information is available, however, on the dielectric properties of grain kernels.

To facilitate reference to data on dielectric properties of grain and related commodities in the literature, Table I identifies sources of information for particular materials. The moisture contents, frequencies, temperatures for which data are presented, and other factors that were considered are also listed.

DISCUSSION AND CONCLUSIONS

Of all the factors that affect the dielectric properties of grain, moisture content has the greatest influence at any given frequency. The dielectric properties also vary greatly with frequency, and, over a wide enough frequency range, the variation of dielectric properties with frequency can exceed even the variation with moisture content.

The dielectric constant varies monotonically with moisture content, increasing in value with moisture content at any given frequency. The dielectric constant decreases in value with increasing frequency.

The dielectric loss factor and loss tangent behave less predictably than does the dielectric contant and may either increase or decrease with frequency or with moisture content, depending upon the particular range of frequency or moisture content.

Grain bulk density appears to be the next most important factor influencing the dielectric properties. For a given lot of grain at a given moisture content, the dielectric properties appear to be nearly linearly related to bulk density over normal density ranges and to have positive density coefficients. Relationships between dielectric properties and bulk density among different lots of the same kind of grain are difficult to establish because of variation among lots in other factors such as kernel size, shape, density, chemical composition, and equilibrium moisture content. Furthermore, bulk density is dependent upon moisture content.

Dielectric properties of grain are also dependent upon temperature. The dielectric constant is almost linearly related to temperature and has a positive temperature coefficient. The loss tangent and loss factor may have either negative or positive temperature coefficients, depending upon frequency, moisture content, and temperature ranges.

Other factors, such as variation in chemical composition and sorption-desorption cycles appear to have smaller influences on the dielectric properties of grain than density and temperature do. Influences of foreign matter and spoilage have not been adequately studied and reported. Differences in oven methods and techniques for determining the reference moisture contents must be taken into account when comparing data on dielectric properties from different sources. Possible differences in measured dielectric properties caused by dielectric nonhomogeneity and different electrode spacings should also be kept in mind.

The inherent variability of dielectric properties of a particular kind of grain can probably be characterized by coefficients of variation of about 5% or less for the dielectric constant, which is the least variable of the dielectric properties. The dielectric constant is also the best single dielectric property to use as an indicator of grain moisture content because of its predictable behavior.

With regard to moisture measurement, the accuracy of instruments utilizing the dielectric constant for this purpose should not be limited to the variability of the dielectric constant. For example, the capacitance of a measurement cell should have less variability for a grain sample of given weight than that associated with the dielectric constant. That is, if the measurement cell is not completely filled by the sample, variation in packing density should have less influence on cell capacitance than on the dielectric constant per se. Variation in packing density should be somewhat self-compensating with respect to cell capacitance, because denser packing, although increasing capacitance because of increased dielectric constant, reduces the effective area of that portion of the capacitor with grain as the dielectric, thus reducing capacitance. Then, too, proper instrument design and use can minimize packing-density variation, and corrections can be applied for sample variation in bulk density.

From the data presented and referenced in this paper, good estimates of the dielectric properties of several kinds of grain can be obtained. If very accurate information on the dielectric properties of particular materials is needed, however, that information can be obtained only by measurements on those materials under the specific conditions required.

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