The Canadian society for engineering in agricultural, food, and biological systems

CSAE

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La société canadienne de génie agroalimentaire et biologique

Paper No. 05-047

DIELECTRIC PROPERTIES MEASUREMENT OF BULK WHEAT SAMPLES USING REFLECTION AND TRANSMISSION TECHNIQUES

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Written for presentation at the
CSAE/SCGR 2005 Meeting
Winnipeg, Manitoba
June 26 - 29, 2005

Abstract Dielectric properties are the intrinsic properties of material, which explain their interaction with electromagnetic energy. Two measurement techniques (i.e., reflection and transmission) for measuring dielectric properties of bulk wheat samples were implemented. An Open-ended coaxial probe was used with Impedance/Vector network analyzer was used for measuring reflection coefficients. The transmission measurements were made using horn antennas with vector network analyzer. An open-ended coaxial probe did not succeed in measuring dielectric properties of bulk wheat samples, because the dielectric constant measured using coaxial probe was highly variable ranging from 1.2 to 6.7. The dielectric loss factor values however, were in the expected range (0.1 to 1) but the trend was highly variable. The dielectric constant values increased rather decreased with the increase in frequency and ranged from 0.65 to 0.95. The results also indicated a noisy pattern of dielectric loss factor values ranging from 0.7 to 6.

Key words: Dielectric constant, dielectric loss factor, permittivity, wheat.

INTRODUCTION

Dielectric properties are the intrinsic properties of a material and depend on its chemical and molecular structure. The area of dielectric properties is a broad field even when limited to grains, because it depends not only on the nature of the material but also on other environmental related parameters such as frequency, temperature, moisture content and density (Nelson 1973). Interest in dielectric properties of agricultural materials has increased as the agricultural technology has become more sophisticated, as new uses for electromagnetic signals are being developed, and new methods, processes, and devices are being developed (Nelson 1973).

Canada produces approximately 60 million tonnes of grain and oilseeds annually. Accurate measurement of moisture content and maintaining the optimum moisture content of grains are important operations in grain storage. Since the dielectric properties of grains are strongly dependent on their moisture content, several moisture meters have been developed for grains using their dielectric properties. As dielectric properties of grains describe the behaviour of grains when subjected to high frequency or microwave electric fields, they can be used to design dielectric heating applications for grain drying, control of insects and seed treatment to improve germination (Nelson 1965).

Interest in the electrical properties of grains dates back more than 95 years. Briggs (1908 cited in Nelson 1973) found a logarithmic increase in electrical resistance as the moisture content of grain decreased. This indicated that moisture content can be determined by an electrical measurement. Briggs (1908) also found a nonlinear increase in electrical resistance as temperature decreased.

Direct current (DC) conductivity of grain was used in earlier instruments for measuring the moisture content of grains (Briggs 1908). Later, alternating current (AC) was used by placing wheat and rye samples between capacitor plates and the capacitance was correlated to the moisture content of grain (Burton and Pitt 1929). The dielectric properties of grain were quantitatively first reported in 1953 along with a reliable method to determine these properties in the 1 to 50 MHz frequency range (Nelson et al. 1953). After that, many researchers measured the dielectric properties of grains in different frequency ranges.

Since bulk grain is a mixture of grain particles and air, measurement of the dielectric properties is more difficult than if it were a homogeneous substance consisting of grain only. There is a need for better understanding of the usefulness and measurement techniques of dielectric properties of grains to develop new sensing devices for the automation of moisture content measurements and design of drying methods. The objective of this research was to investigate the feasibility of reflection and transmission techniques for measuring dielectric properties of bulk wheat samples using open-ended coaxial probe and free space measurement setup, respectively.

DEFINITIONS AND PRINCIPLES

Dielectric properties

A dielectric is a material that is a poor conductor of electricity which supports an electric field. Nearly all materials including biological materials except ferro-electrics belong to this class. Dielectric properties are expressed in terms of dielectric constant ($\varepsilon`$) and dielectric loss factor ($\varepsilon``$). Often a dissipation factor ($\tan\delta$) is also used as a descriptive factor of dielectric properties.

A dielectric medium placed between the parallel plates of a capacitor has the ability to increase the capacitance of the capacitor. To specify this property, permittivity is defined, usually noted by the symbol ε, and ε_o for the free space.

$$C = \varepsilon\, a/d \tag{1}$$

where,

C = capacitance of the capacitor (F)

ε = permittivity of the dielectric medium (F/m)

a = area of the parallel plates (m^2)

d = distance between the parallel plates (m)

Permittivity is the fundamental electrical property which describes the interactions of electro magnetic properties of materials.

The dielectric properties of usual interest are the dielectric constant $\varepsilon`$ and the dielectric loss factor $\varepsilon``$, the real and imaginary parts of the relative complex permittivity.

$$\varepsilon = \varepsilon` - \varepsilon`` \tag{2}$$

$$\varepsilon = |\varepsilon| e^{-j\delta} \tag{3}$$

where,

δ = loss angle of the dielectric (radians)

The dielectric constant is a measure of the ability of the material to store electrical energy, while, the loss factor is a measure of the energy absorbed from the applied electric field.

Every material has a relative permittivity (ε_r) (Bekefi and Barrett 1977). In practice the subscript 'r' and the term relative are often omitted. Relative permittivity is the ratio of the permittivity of the substance to the permittivity of free space.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \tag{4}$$

where,

ε_r = dielectric constant or relative permittivity,

ε = permittivity of dielectric material, and

ε_o= permittivity of free space = 8.54×10^{-12} F/m.

ε is always greater than or equal to ε_o, so the relative permittivity is greater than or equal to unity. Relative permittivity values may be differentiated from absolute values because relative permittivity is generally a number greater than or equal to unity, whereas absolute values include a negative power of ten.

MEASUREMENT TECHNIQUES

Various measurement techniques have been developed for measuring the dielectric properties of different agricultural materials (Nelson 1999). The measurement technique is usually determined by the nature of the test material, frequency and temperature range in which the measurement is to be made. In principle, dielectric properties measurement techniques can be broadly divided into two categories namely, reflection and transmission techniques. In this study, an open-ended coaxial probe method was used as a reflection technique and a free-space transmission measurement technique was used as a transmission technique for measuring dielectric properties.

MATERIALS AND METHODS

Sample preparation

Hard red winter (HRW) wheat was obtained from Cereal Research Centre of Agriculture and Agri-Food Canada, Winnipeg at an initial moisture content of 11.9% (wet basis). Then the sample of 10 kg was adjusted for moisture content by adding the required amount of distilled water and mixing it in a rotating drum to bring the moisture content to 14% (wet basis). After adding water, the samples were sealed in polythene bags and stored in a refrigerator for 72 h for uniform moisture distribution. Samples were mixed within the bag every 3 h to ensure the uniform distribution of moisture.

Coaxial probe method

A sample holder and temperature control assembly was designed for use with the coaxial probe (Nelson et al. 1997). A stainless steel cup, 18.95 mm inside diameter and 19 mm deep was used as a sample holder which was already mounted in a Delrin water jacket with an O-ring seal. The water jacket was connected with latex rubber tubing to a constant-temperature liquid circulator (RMT 6, Brinkmann/Lauda, Lauda, Germany). Water was used as the heat transfer liquid. Sample temperature was measured with a thermocouple inserted to the bottom of a 15 mm deep 1 mm diameter hole drilled vertically into the 1.65 mm thick side wall of the sample cup. The thermocouple was connected to a thermocouple indicator to read temperature directly.

The dielectric properties of bulk wheat samples were measured over the frequency range from 0.02 GHz to 3 GHz at 24°C with an open-ended coaxial probe (Hewlett-Packard 85070D, Agilent, Santa Clara, CA) and impedance analyzer (Agilent E4991A, Agilent, Santa Clara, CA); and with vector network analyzer (Anritsu 360B, Anritsu, Ottawa, ON) it was measured over the frequency range from 0.04 GHz to 3 GHz. The open-ended coaxial probe was connected to the Impedance or Vector network analyzer using a coaxial cable. General purpose interface board (GPIB) was used to connect Impedance or Vector network analyzer to the computer. The experimental setup is shown in Figure 1. Before starting the dielectric properties measurements, the calibration of the impedance analyzer or vector network analyzer was performed. In the case of the impedance analyzer, the analyzer was calibrated using short, open, standard load (distilled water) and compensation for low-loss capacitance. In the case of the vector network analyzer, the analyzer was calibrated by the reflection only (1-port) calibration method. Then the S_{11} parameters of air (S_{o11}), short circuit (S_{s11}), and distilled water (S_{w11}) were measured (Kato et al. 2004).

The bulk wheat sample was inserted into the sample cup, and the sample cup and water jacket assembly was raised with its supporting platform for the probe to enter the sample cup and make firm contact with it. Dielectric properties measurements were then performed at 24°C.

With the impedance analyzer, software provided by Agilent was used to convert the measured reflection coefficients to complex dielectric properties. In the case of the vector network analyzer the following equation was used to convert the S_{11} parameters to dielectric properties (Kato et al. 2004).

$$\varepsilon_m = \frac{\varepsilon_w (S_{m11} - S_{o11})(S_{s11} - S_{w11}) + (S_{m11} - S_{w11})(S_{o11} - S_{s11})}{(S_{m11} - S_{s11})(S_{o11} - S_{w11})} \tag{7}$$

where,

ε_m = complex permittivity of the material

ε_w = complex permittivity of distilled water

S_{m11} = S_{11} parameter of the material

S_{w11} = S_{11} parameter of distilled water

S_{o11} = S_{11} parameter at probe-open (air)

S_{s11} = S_{11} parameter at probe-short

Free space method

The sample holder was a Styrofoam box of rectangular cross section with a wall thickness of 2.5 cm. The internal dimensions of the sample holder were 25 cm in length, 25 cm in height and 16 cm in thickness. Different thicknesses were obtained by placing Styrofoam sheets inside the box.

The two horn antennas were placed facing each other 37 cm apart. Both antennas were connected to the vector network analyzer using two coaxial cables with APC-7 connectors at their terminations. The experimental setup is shown in Figure 2. Before starting the measurements, the vector network analyzer was calibrated by 1-path, 2-port calibration method. The scattering transmission coefficients (S_{21} parameters) of the empty sample holder were measured by placing the sample holder midway between the two antennas. The sample holder was filled with wheat and the S_{21} measurement was performed again. From these two measurements the S_{21} parameters of wheat were calculated. The dielectric constant and loss factor were computed from the transmission coefficients of the sample using the following equations (Trabelsi and Nelson 2003):

$$\varepsilon' = \left(1 + \frac{\Phi\lambda_0}{360\mathrm{d}}\right)^2 \tag{8}$$

$$\varepsilon'' = \frac{\mathrm{A}\lambda_0}{8.686\pi.}\sqrt{\varepsilon'} \tag{9}$$

where,

ϕ = phase shift (degrees) $\phi = \varphi - 2\pi n$

λ_0 = frequency at free space (Hz)

A = attenuation (dB) $A = 20 \log |S_{21}|$

d = thickness of the sample (m)

φ = phase of transmitted wave (degrees)

The integer n can be computed by performing measurements at two frequencies (Trabelsi et al. 2000). Also, it can be computed by repeating the measurements with samples of different thicknesses (Musil and Zacek 1986). The dielectric constant and loss factor calculated with equations (8) and (9) were the average values for the entire sample, assuming the physical properties are the same throughout the sample.

RESULTS AND DISCUSSIONS

Coaxial probe method

Fifty replications were done using the coaxial probe method. Four of those 50 measurements are presented in Figures 3 and 4 where the frequency dependence of the measured dielectric constant and dielectric loss factor are shown. From the literature data, it was expected that the dielectric constant of the bulk wheat samples should be decreased with the increase in frequency and the loss factor should increase or decrease with the increase in frequency. But the results of the dielectric properties measurements using the open ended coaxial probe with the impedance or vector network analyzer were highly variable ranging from 1.2 to 6.7. Though the dielectric loss factor values are in the expected range (0.1 to 1), the trend is highly variable. The bulk wheat constitutes an extremely non-homogeneous dielectric (larger air gaps) for this type of measurement. Therefore, the variability is likely due in large part to variation in the effective density of the sample in the small region (3 mm diameter) at the open end of the coaxial line probe from which the reflected energy is used for the permittivity determination. Problems of resonance due to reflections from the dielectric interfaces at the sample and sample cup boundaries may also have caused this variability. When water was used as a sample such variability was not notice because of nice contact between probe and liquid water.

Free space method

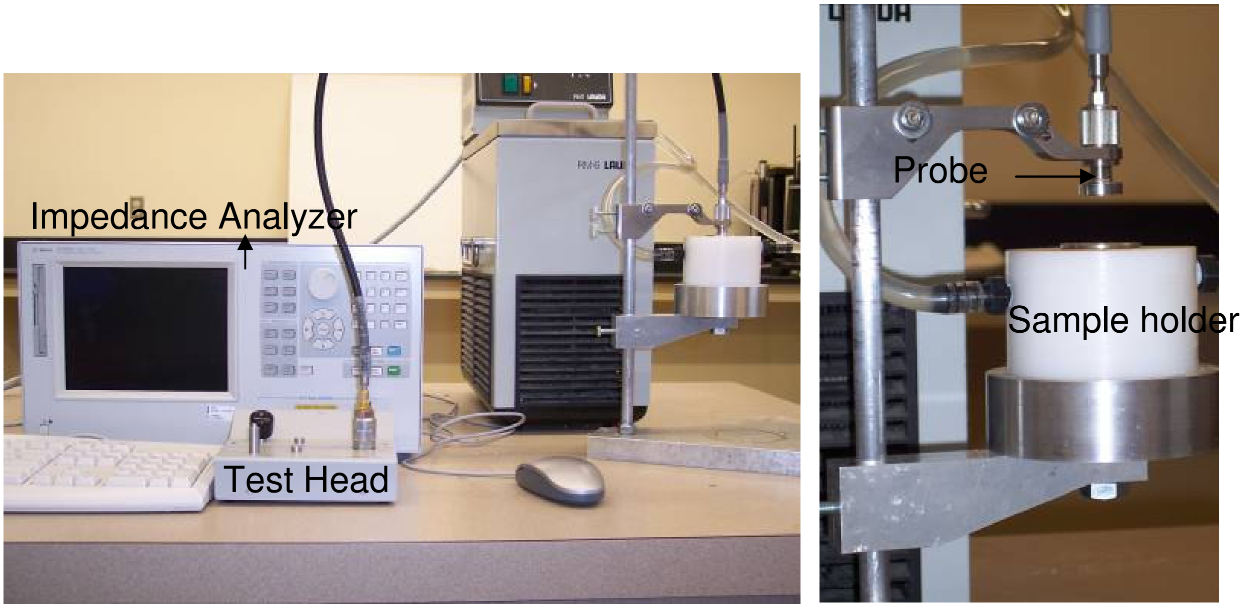
Results of the dielectric properties measurements at various thicknesses of bulk wheat sample are presented in Figures 5 and 6. Thirty one replications were done for this method. The results were consistent but it was expected that the dielectric constant of bulk wheat should decrease with the increase in frequency. There is a wavy trend found in the dielectric constant measurement which increases with the increase in frequency ranging from 0.65 to 0.95. That is because of the post calibration mismatches and possible multiple path transmission. It was expected that the dielectric loss factor should be ranging from 0.1 to 1. But the results indicate a noisy pattern ranging from 0.7 to 6. Time domain gating should be applied to ensure that there are no multiple reflections inside the sample, though the thickness of the sample was chosen to avoid it. Without time domain gating, horn antennas alone cannot be used with the vector network analyzer for measuring dielectric properties of bulk wheat due to diffraction of energy from the edges of horn antennas. Since bulk wheat is non-homogeneous in nature, multiple reflections within the sample may also be the other reason for these unexpected results.

CONCLUSIONS

An open-ended coaxial probe technique is not suitable for reliable determination of the dielectric properties of bulk wheat. It can only be used for homogeneous materials such as liquid foods. Lens antennas can be used with horn antennas to concentrate the energy into the sample so that the planar wave would be normally incident to the surface of the sample which would avoid the edge diffractions. Time domain gating should be applied to eliminate the post calibration mismatches and multiple path transmissions.

ACKNOWLEDGEMENTS

Authors thank the Canada Research Chairs program for funding this study. We would like to thank Dr. Giuseppe (Joe) LoVetri and Dr. Gabriel Thomas for providing the facility to carry on this study. We also thank the technicians Mr. Dale Bourns, Mr. Gerry Woods, Mr. Matt McDonald, and Mr. Brad Tabachnick for their help in the experimental setup.



(a) **(b)**

Figure 1. (a) Coaxial probe measurement setup (b) Sample holder and probe

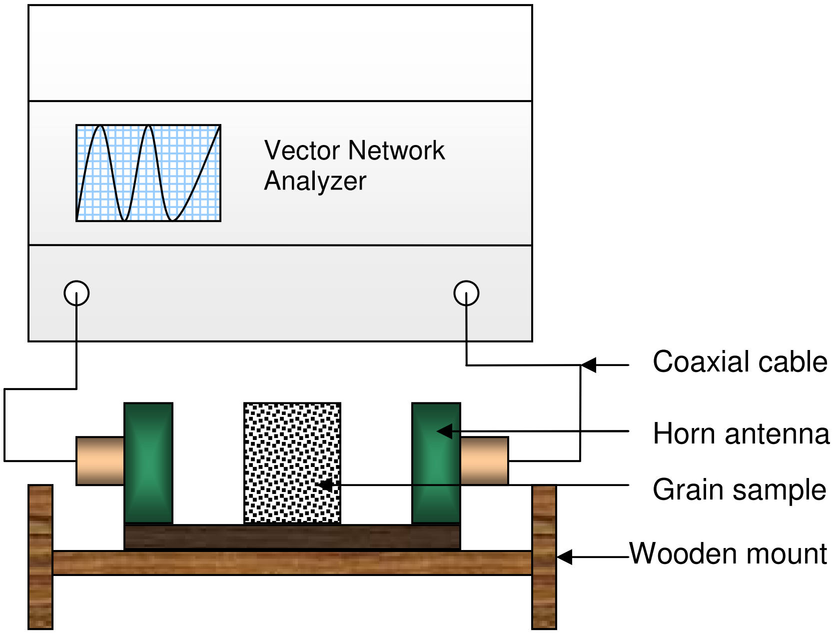


Figure 2. Transmission line (free space method) measurement setup

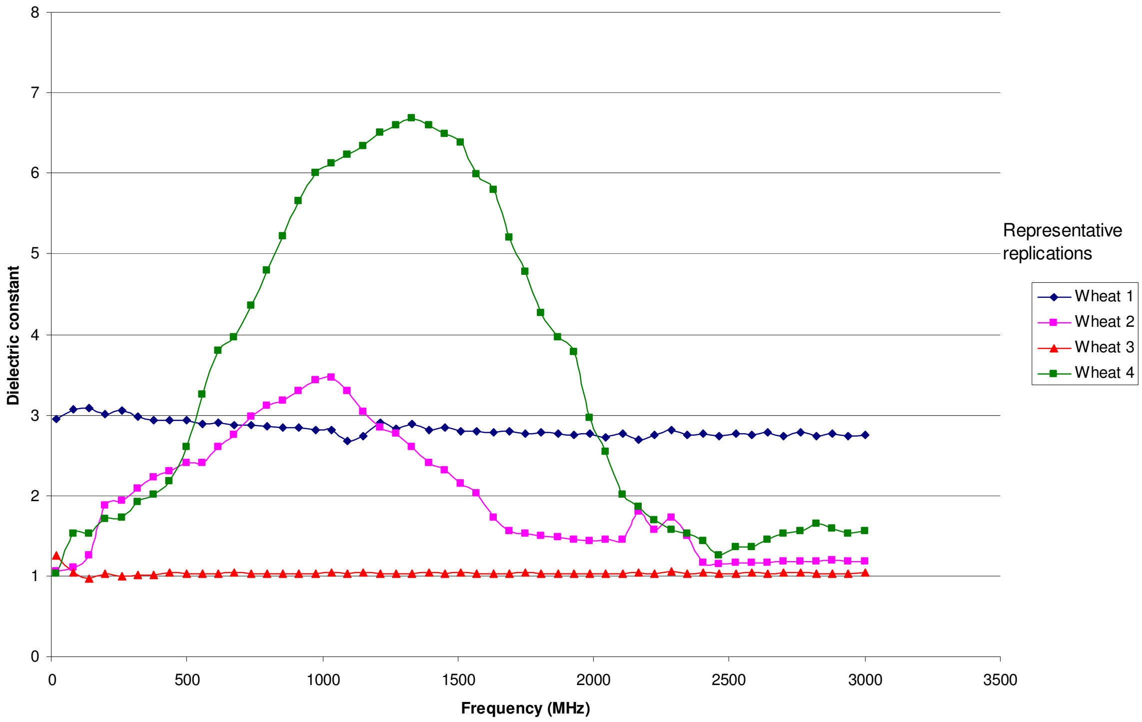


Figure 3. Dielectric constant of bulk wheat sample (coaxial probe method)

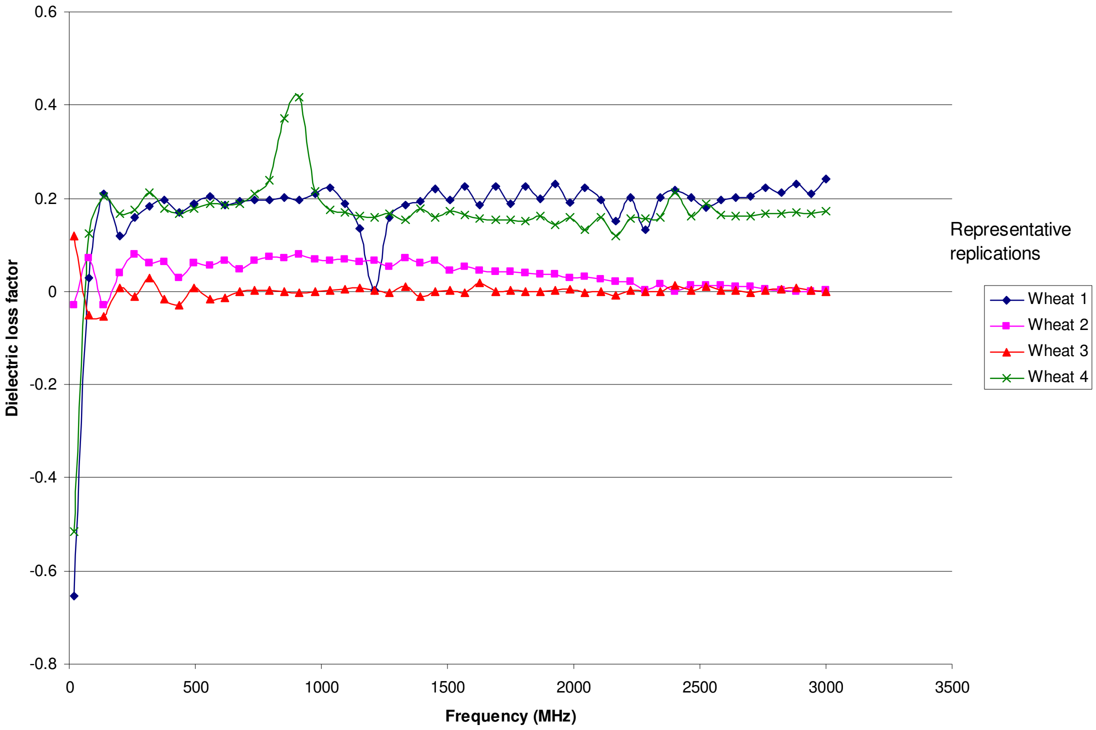


Figure 4. Dielectric loss factor of bulk wheat sample (coaxial probe method)

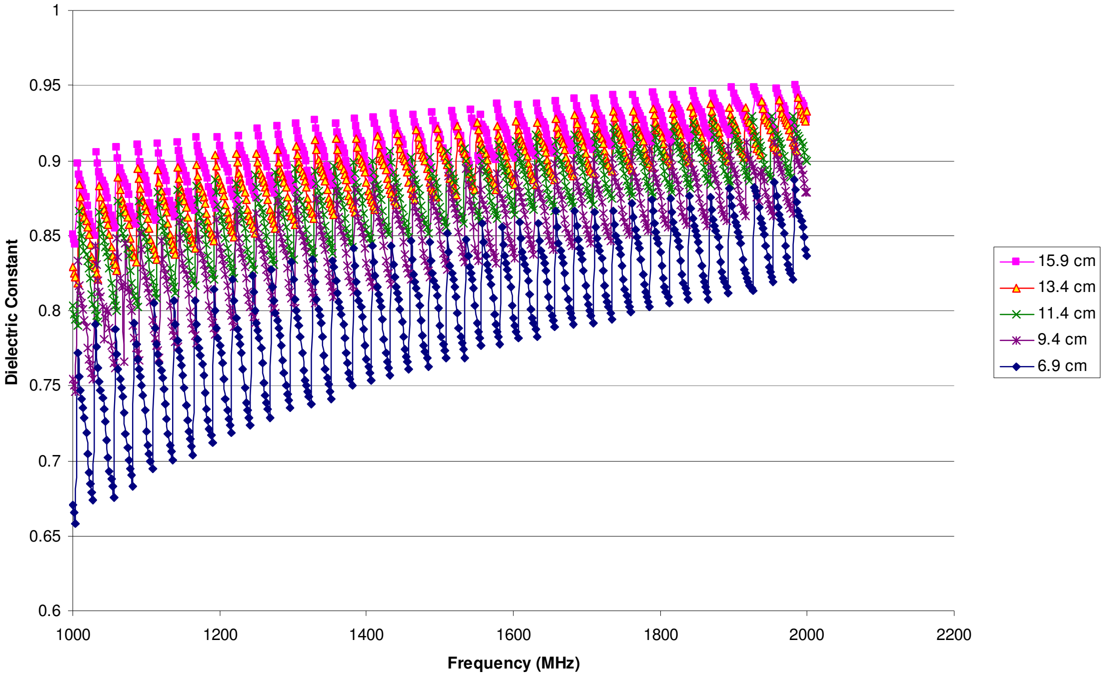


Figure 5. Dielectric constant of bulk wheat sample (free space method) at different thicknesses

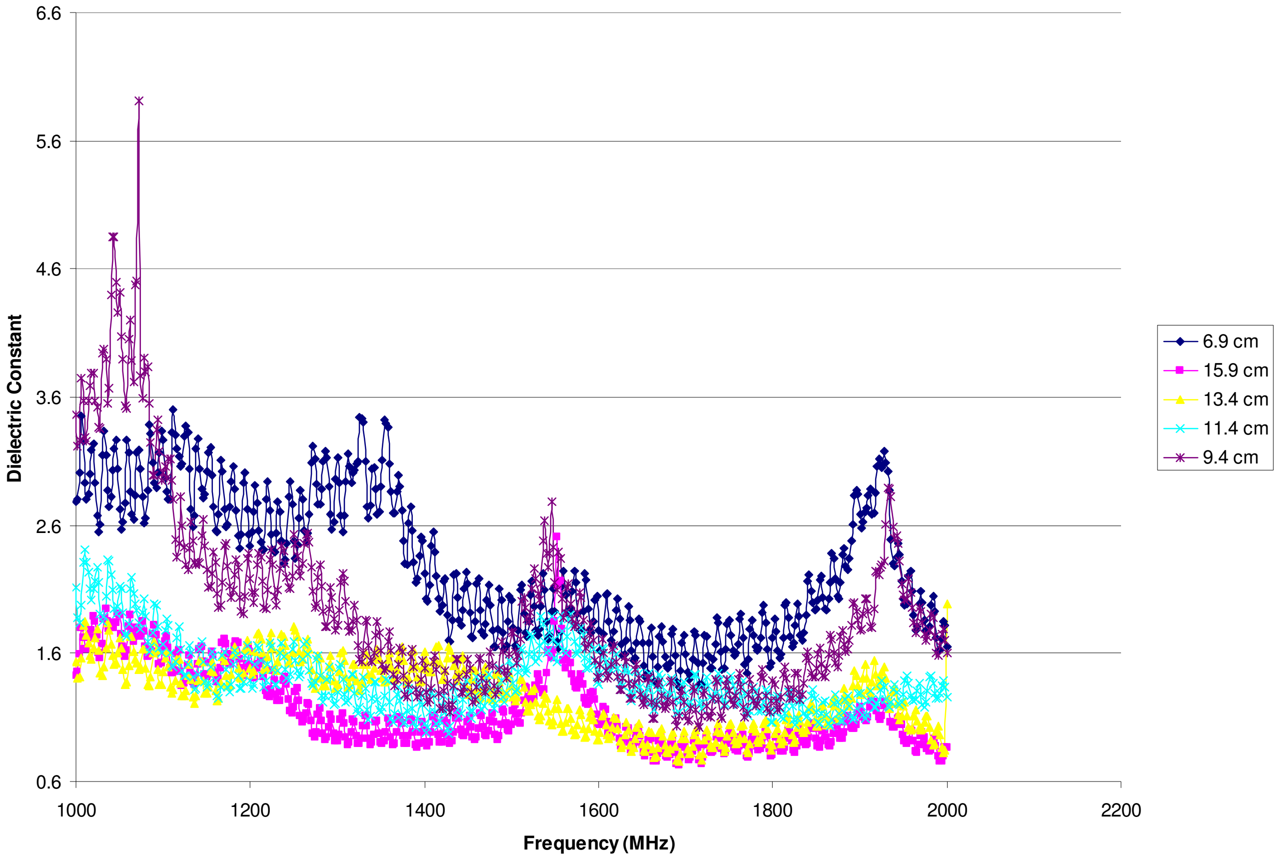


Figure 6. Dielectric loss factor of bulk wheat sample (free space method) at different thicknesses

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