Assessment of Reflection and Transmission Techniques for Determining Dielectric Properties of Bulk Wheat Samples

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Master of Science

By

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"Assessment of Reflection and Transmission Techniques for Determining Dielectric Properties of Bulk Wheat Samples"

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

MASTER OF SCIENCE

Dedicated To

My Beloved Parents and Brother

ABSTRACT

Dielectric properties are an intrinsic property of a 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 assessed. An open-ended coaxial probe with impedance and vector network analyzer was used for measuring reflection coefficients. With impedance analyzer, the dielectric properties of bulk wheat samples were measured over the frequency range from 0.02 GHz to 3 GHz and with network analyzer, the measurements were done at the frequency range from 0.04 GHz to 3 GHz. An open-ended coaxial probe did not succeed in measuring dielectric properties of bulk wheat samples, because the dielectric constant measured using the 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 transmission measurements were made using horn antennas with a vector network analyzer. The measurements were done at the frequency range from 1 GHz to 2 GHz. The dielectric constant values measured by using transmission methods were increased rather than decreased with an 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. The noise may due to the multiple reflections inside the sample.

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1. INTRODUCTION

1.1. Purpose of the Research

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 1973a). Interest in dielectric properties of agricultural materials has increased as the agricultural technology has become more sophisticated, new uses for electromagnetic signals are being developed, and as new methods, processes, and devices are being developed (Nelson 1973a).

Canada produces approximately 60 Mt (million tonnes) of grains and oilseeds annually. Accurate measurement of the 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 grain 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 1973a) found a logarithmic increase in 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 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 automation of moisture content measurements and design of drying methods.

In this work, it was decided to investigate the feasibility of reflection and transmission techniques for measuring dielectric properties of bulk wheat samples using dielectric probe and free space measurement setup, respectively. The experimental data have been presented to illustrate the limitations of both methods.

2. DEFINITIONS AND PRINCIPLES

2.1. 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 a dielectric constant ($\varepsilon`$) and the 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 denoting the permittivity of free space.

$$C = \varepsilon\, a/d \qquad (1)$$

where,

C = capacitance of the capacitor (F),

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

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

d = distance between the parallel plates (m).

Permittivity is the fundamental electrical property which describes the interaction of a material with the applied electromagnetic field.

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.

$$\varepsilon = \varepsilon` - j\,\varepsilon`` \quad (2)$$

$$\varepsilon = |\varepsilon|\, e^{-j\delta} \quad (3)$$

where,

δ = loss angle of the dielectric (rad).

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.

Dissipation factor or the loss tangent ($\tan \delta$) can be defined in terms of $\varepsilon`$ and $\varepsilon``$.

$$\tan \delta = \frac{\varepsilon``}{\varepsilon`} \quad (4)$$

Sometimes the power factor is also used as a descriptive dielectric parameter.

$$\text{Power factor} = \frac{\tan \delta}{\sqrt{1 + \tan^2 \delta}} \quad (5)$$

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.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \quad (6)$$

where,

ε_r = dielectric constant or relative permittivity,

ε = permittivity of dielectric material (F/m), and

ε_o= permittivity of free space = 8.854×10^{-12} F/m.

For most materials, ε is always greater than or equal to ε_o, so the relative permittivity is greater than or equal to unity (Trapp 1976). 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.

To understand the dielectric phenomenon, it is necessary to understand the mechanisms of polarization that contribute to energy storage and losses.

2.2. Polarization

Molecules of a dielectric medium may have positive and negative charges, separated by a distance, called dipoles. When a dielectric medium is placed between two parallel plates connected to a direct electromotive force, the dipoles align along the lines of the field existing between the plates. This process of alignment of electrical dipoles within a dielectric medium placed in an electric field is called as polarization. The result of polarization is the formation of chains of alternating positive and negative charges from one plate to the other. The charges near to the capacitor plates neutralize some of the charges on the plates of the capacitor, allowing a greater charge to be stored on the plates.

There are four different sources of polarization that affect the dielectric properties of a material (Trapp 1976):

1. Orientational polarization
2. Electronic polarization

3. Atomic polarization
4. Interfacial polarization

Therefore, the total contribution of polarization to the dielectric constant is a summation of the above four sources.

2.2.1. Orientational polarization

Materials that have no centre of symmetry for positive and negative charges in their molecular structure have permanent dipoles. In an external electric field, these permanent dipoles will attempt to align along the field by rotation. This is known as orientational polarization. As the temperature rises, the possible alignment of dipoles lessens by the thermal agitation. Therefore, the contribution of orientational polarization to the dielectric constant decreases as temperature increases.

2.2.2. Electronic polarization

Under the influence of an applied electric field, the shifting of electrons relative to the nucleus occurs which creates small dipoles. In spite of the large number of atoms in the material, this polarization effect is small.

2.2.3. Atomic polarization

In an external electric field, by a displacement of atoms within the molecule, dipoles are created. Effect of this polarization is also very small compared to orientational polarization. As the above two types of polarization involve distortion of centre of charge symmetry of the base atom, these two forms are known as induced or distortional polarization.

2.2.4. Interfacial polarization

Interfacial polarization occurs when free charge carriers, such as ions, build up along defects and interfaces in the structure of the dielectric material. The effect may be quite large at low frequencies (below a few kHz) but usually diminishes rapidly with increasing frequency.

As finite time is required for the alignment of the dipoles in an external electric field, the mechanisms of polarization are frequency dependent when an alternating electro-motive force is applied to create the electric field. As the frequency increases the alignment of the dipoles begins to lag. The contribution to polarization of the dielectric decreases and losses occur. This decrease in the dielectric constant is termed dispersion, while the increase in losses is called dielectric absorption.

Interfacial polarization is the first mechanism to be affected by increasing frequency and the next mechanisms to be affected, in descending order, are orientational, atomic and electronic polarization.

All materials can be classified into three groups, namely non-polar, polar and dipolar according to the type of polarization they display under the influence of an electric field. Non-polar materials, usually pure elements, show electronic polarization with dispersion at optical frequencies. Polar materials have a polar moment induced under an applied field with dispersion in the infrared as well as the optical region. Dipolar materials which have permanent polar moments exhibit orientational polarization as well as the interfacial and atomic polarization.

2.3. Factors affecting dielectric properties

As most agricultural materials are heterogeneous in nature, the amount of water in the materials is a dominant factor. In granular or particulate materials such as grains, the bulk density of the air-particle mixture is another factor that influences their dielectric properties. The dielectric properties also depend on the frequency at which the measurement is made, temperature of the materials, and the chemical composition of the materials.

2.3.1. Moisture content

Water in biological materials exists as either bound or free water. Bound water is tightly held by the molecules of starch, protein and other components of grain and forms part of the physical structure of the molecules. The dielectric constant of bound water is similar to that of ice. At low moisture contents almost all of the water in grain may be bound water, while at higher moisture contents free water predominates. At low frequencies, the value of the dielectric constant of free water is close to 80 while that of bound water is in the order of 4.5 to 5.0 (Trapp 1976). Although water is a dipolar substance characterized by a high polar moment, in the bound form, it is restricted in its rotation in an alternating field. This is the reason for the large difference in the dielectric constants of the two forms of water.

2.3.2. Frequency

Dielectric properties of most materials, except for some low loss materials which absorb no energy from radio frequency (RF) and microwave fields, vary considerably with the frequency of the applied electric field. The main reason behind the frequency dependent nature of dielectric measurements is the process of polarization. Polarization is the process of alignment of electrical dipoles within a dielectric medium placed in an electric field. The mechanisms of polarization are frequency dependent since a finite time is required for the realignment of the dipoles in the applied alternating field. As the frequency increases the alignment of the dipoles begins to lag. The contribution to polarization of the dielectric decreases and losses occur. This decrease in the dielectric constant is termed dispersion, while the increase in losses is called dielectric absorption.

Debye(1929) described this process for pure polar material using the following equation:

$$\varepsilon = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + j\omega\tau} \qquad (7)$$

where,

ε_{∞} = dielectric constant at resonant frequencies (frequencies so high that molecular orientation does not have time to contribute to the polarization)

ε_s = static dielectric constant (the dielectric constant at zero frequency)

τ= relaxation time, (the time taken by the dipoles to return to random orientation when the external electric field is removed).

Separation of equation (7) into its real and imaginary parts yields:

$$\varepsilon` = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + \omega^2\tau^2} \qquad (8)$$

$$\varepsilon`` = \frac{(\varepsilon_s - \varepsilon_{\infty})\omega\tau}{1 + \omega^2\tau^2} \qquad (9)$$

where,

ω=relaxation frequency ($\omega = 1/\tau$)

Thus, any material, at zero and resonant frequencies has constant dielectric constant values and at intermediate frequencies the dielectric constant decreases with an increase in frequency. Losses are zero at zero and resonant frequencies but at intermediate frequencies the dielectric losses occur with the peak loss at the relaxation frequency (Nelson 1991).

2.3.3. Temperature

As the temperature rises, increased thermal agitation lessens the possible alignment of dipoles, resulting in a decrease in relaxation time. Thus in the region of dispersion, the dielectric constant will increase with increasing temperature, whereas the loss factor may either increase or decrease, if operating frequency is higher or lower than the relaxation frequency. At frequencies below the region of dispersion, the dielectric constant decreases with increasing temperature. The frequency and temperature dependent behaviour of the dielectric properties of most materials is complicated and can only be determined by measurement at the frequency and temperature of interest. There are several reviews of the dielectric properties of food and agricultural products at microwave frequencies (Bengtsson and Risman 1971; Nelson 1973b; Ohlsson and Bengtsson 1975; Kent 1987). The dielectric properties of liquid water at microwave frequencies are given in Table 1 at temperatures of 20 and 30°C.

2.3.4. Density

Since the influence of a dielectric material depends on the amount of mass interacting with the electromagnetic fields, the mass per unit volume (bulk density) has an effect on the dielectric properties (Nelson 1992). This is especially notable with pulverized or granular materials. In understanding the nature of the bulk density dependence of the dielectric properties of particulate materials, relationships between the dielectric properties of solid materials and those of air-particle mixtures are useful.

Table 1. Dielectric properties of water at indicated temperatures and frequencies in the microwave spectrum (Hasted 1973).

Frequency (GHz)	Temperature (°C)			
	20		30	
	ε'	ε''	ε'	ε''
0.577	80.3	2.8	69.9	1.3
1.744	79.2	7.9	69.7	3.6
3.000	77.4	13.0	68.4	5.8
4.630	74.0	18.8	68.5	94
9.140	63.0	31.5	65.5	16.5
9.370	62.0	32.0	64.5	17.0
12.470	-	-	61.5	21.4

In some instances, the dielectric properties of a solid may be needed but particulate samples are the only available form of the material. This is true for cereal grains, where kernels are too small for the dielectric sample holders used for measurements (Nelson and You 1989) and in the case of pure minerals that had to be pulverized for purification. For some materials, fabrication of samples to exact dimensions required for dielectric properties measurement is difficult, and measurements on pulverized materials are more easily performed. In such instances, proven relationships for converting dielectric properties of particulate samples to those for the solid material are important. Several dielectric mixture equations have been developed and evaluated for this purpose (Nelson and You 1989).

The notation used below applies to a two-component mixture, where ε represents the effective permittivity of the mixture, ε_1 is the permittivity of the medium in which particles of permittivity ε_2 are dispersed, and v_1 and v_2 are the volume fractions of the respective components, where $v_1 + v_2 = 1$. Two of the mixture equations found to be particularly useful for cereal grains are: the complex refractive index mixture equation (Nelson 1991):

$$\varepsilon^{1/2} = v_1\varepsilon_1^{1/2} + v_2\,\varepsilon_2^{1/2} \tag{10}$$

and the Landau and Lifshitz, Looyenga equation (Nelson 1991):

$$\varepsilon^{1/3} = v_1\varepsilon_1^{1/3} + v_2\varepsilon_2^{1/3} \tag{11}$$

To use these equations to determine ε_2, one needs to know the dielectric properties of the pulverized sample at its bulk density, and the specific gravity or density of the solid material. Nelson (1991) reported that the two equations (Equations 10 and 11) provide a relatively reliable method for adjusting the dielectric properties of granular and powdered materials from known values at one bulk density to corresponding values for a different bulk density. The differences due to bulk density follow expectations due to differences in the air occupied volume.

Nelson (1991) reported that the dielectric properties of various hydro-colloids of solid materials were greater than of the powdered materials. Kent and Kress-Rogers (1986) reported, based on their studies on instant coffee and milk powder, that pure particle size effect on permittivity is possible. Measurement on various sieve fractions of powdered or crushed grains obtained by Venkatesh et al. (1998) also indicated the possibility of a particle size effect. Essentially, when a material is crushed or powdered, one may expect changes in the surface characteristics, and it is, therefore, possible that the proportion of energy transmitted changes. This would be reflected by a change in the dielectric constant, without necessarily a change in the loss factor.

2.3.5. Composition

The dielectric properties of agricultural materials also depend upon their chemical composition. The organic constituents of food are dielectrically inert ($\varepsilon` < 3.0$ and $\varepsilon`` < 0.1$) compared to aqueous ionic fluids or water, and may be considered transparent to energy (Mudgett 1985). Ohlsson et al. (1974) found that for many foods the influence of different water and salt content on dielectric properties was significantly large, especially at 450 and 900 MHz. It was also reported that at temperatures above 60°C, $\varepsilon`$ decreased gently with temperature, whereas $\varepsilon``$ increased, particularly at lower frequencies for salty foods (Bengtsson and Risman 1971). Dielectric properties of some foods at 2.45 GHz and 20 to 25°C have been reported by Buffler and Stanford (1991).

Dielectric properties of aqueous sugar solutions of different concentrations have been measured and compared with those of grapes of similar moisture concentrations (Tulasidas et al. 1995a). In grapes at high moisture, the dielectric constant and loss factor decreased with an increase of temperature and a reverse trend was observed for grapes with low moisture (Tulasidas et al. 1995b).

While alcohols and dissolved carbohydrates are active ingredients in some foods and beverages, their effects on dielectric properties are negligible in most food products, except for high carbohydrate foods, such as bakery products or syrups, and high alcoholic content beverages. The effects are related to stabilization of hydrogen bonding patterns through hydroxyl-water interaction (Kudra et al. 1992). The effects of pH are not believed to be significant by themselves at the pH levels typical in foods (Ohlsson et al. 1974; Mudgett 1986; Nyfors and Vainikainen 1989).

The effect of fat on dielectric properties appears to be that of dilution (more fat, less water). The heating rate seems to have no effect per se on the dielectric properties, unless water and juices are lost. At lower frequencies (450 and 900 MHz), the relationships appear to be similar (Bengtsson and Risman 1971; Ohlsson et al. 1974). The microwave heating characteristics (temperatures rise with time) of extraction mixtures consisting of rosemary or peppermint leaves suspended in hexane, ethanol and hexane plus ethanol mixtures were dependent on the dielectric properties of the solvents and the leaves (Chen and Spiro 1994).

There have been several attempts to develop relationships between the dielectric properties and composition, based on weighted averages of the dielectric properties of individual components (Sun et al. 1995; Kudra et al. 1992). Table 2 shows the permittivity values of milk and its constituents (Kudra et al. 1992). However, these studies imply that the approach is incomplete due to possible synergistic and loss effects. Essentially, cross-binding of components in the parent material seems to play a role that cannot be easily accounted for when measurements are done on the components individually. The dielectric properties and loss factor of four different processed cheeses of four different compositions are shown in Table 3 for temperatures of 20 and 70°C (Venkatesh and Raghavan 2004). At higher and lower fat contents, the loss factor decreased somewhat with temperature.

Table 2. Dielectric properties of milk and its constituents at 2.45 GHz and 20°C (Kudra et al. 1992).

Description	Fat (%)	Protein (%)	Lactose (%)	Moisture (%)	ε'	ε''
1% Milk	0.94	3.31	4.93	90.11	0.6	7.6
3.25% Milk	3.17	3.25	4.79	88.13	8.0	7.6
Water + Lactose I	0.00	0.00	4.00	96.00	78.2	3.8
Water + Lactose II	0.00	0.00	7.00	93.00	77.3	4.4
Water + Lactose III	0.00	0.00	10.00	90.00	76.3	4.9
Caseinate I Water + sodium	0.00	6.48	0.00	93.62	73.0	15.7
Caseinate II Water + sodium	0.00	8.71	0.00	91.29	71.4	15.9
Caseinate III Lactose (solid)	0.00	0.00	100.00	0.00	1.9	0.0
Sodium Caseinate (solid)	0.00	100.00	0.00	0.00	1.6	0.0
Milk fat (solid)	100.00	0.00	0.00	0.00	2.6	0.2
Water (distilled)	0.00	0.00	0.00	100.00	78.0	13.4

Table 3. Dielectric properties of processed cheese at 2.45 GHz as related to composition and temperature (Venkatesh and Raghavan 2004).

Cheese Composition		**Temperature °C**			
		20		**70**	
Fat (%)	**Moisture (%)**	ε'	ε''	ε'	ε''
0	67	43	43	29	37
12	55	30	32	21	23
24	43	20	22	14	17
36	31	14	13	8	6

3. LITERATURE REVIEW

3.1. Requirements for a measurement technique to measure the dielectric properties of biological materials

Several measurement techniques have been developed for measuring the dielectric properties of different kinds of materials (Schwan 1957; 1959; Sucher and Fox 1963; Bengtsson and Risman 1971; Nelson 1972; 1999; Metaxas and Meredith 1983). The use of a particular measurement depends on the nature of the test material, frequency range of interest, temperature in which the measurement is to be made, and degree of accuracy required.

Water in biological materials exists in two forms i.e. as free water and bound water or water of crystallization. The technique selected for measuring the permittivity of wet granular materials should fulfill several requirements, some of which are listed below:

- It should allow measuring the dielectric properties over a wide range of frequency and temperature.
- The required instrumentation, measurement procedure, and necessary calculations should be simple.
- Sample preparation and handling of sample during measurements should be simple so that it would be possible to protect the change in sample density and moisture content during measurements.

3.2. Measurements at low frequencies

Field (1954) reviewed the use of various bridges and resonant circuits and other techniques for permittivity measurements in the low, medium, and high frequency ranges. Capacitance bridges (Schering Bridge) and resonant circuits (Figure 1) are used to determine the dielectric properties at low frequencies (up to 100 MHz). The capacitance bridges used for dielectric measurements usually have two standard variable capacitors (C_N) and one parallel plate setup (C_P) to hold the sample to be measured as shown in Figure 1 (a). The resonant circuits have variable capacitor with fixed inductors as shown in Figure 1 (b).

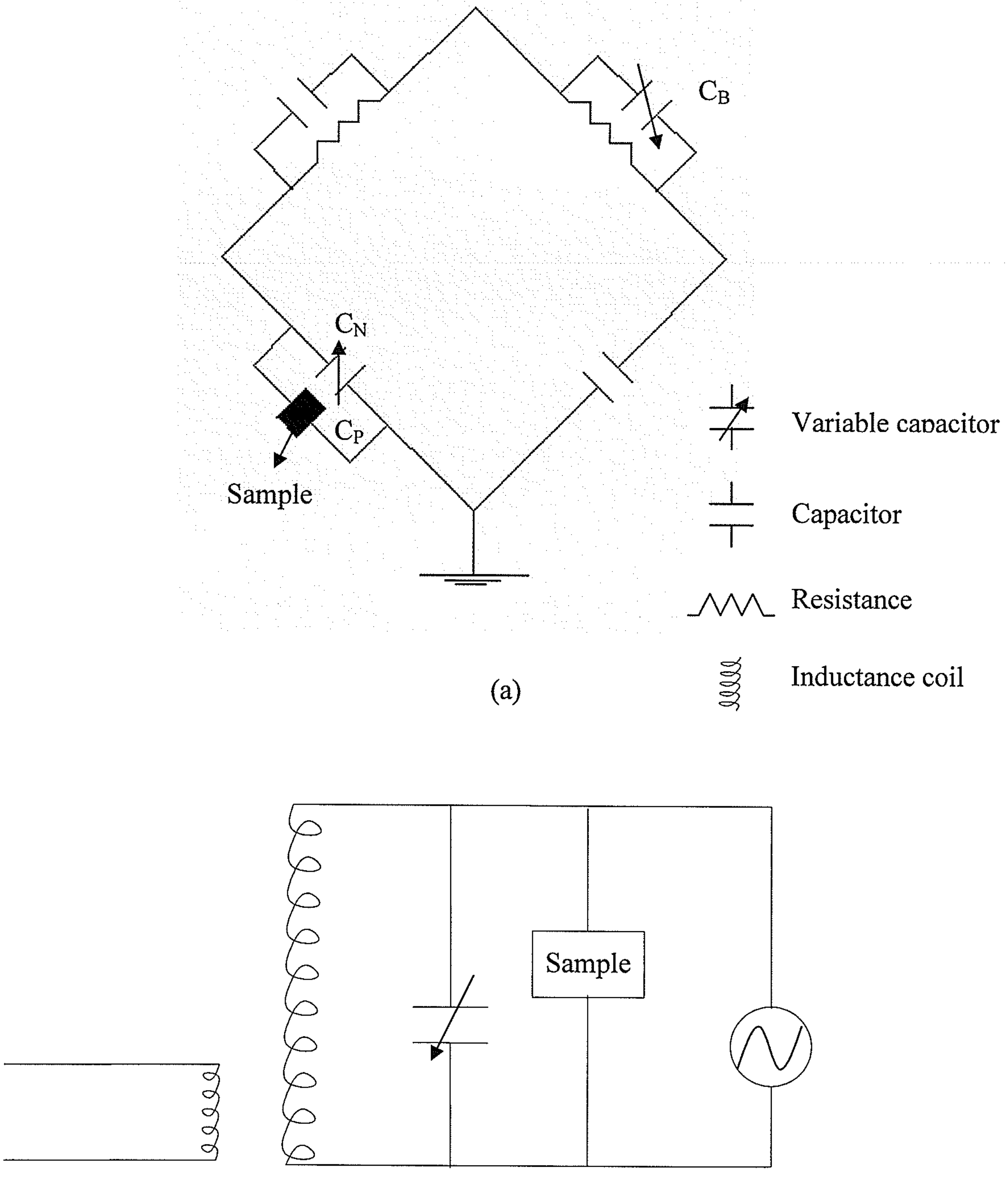
In the capacitance bridge method the dielectric sample is placed in parallel with the standard capacitor (C_N) and the bridge is balanced by adjusting C_N and C_B. Then the dielectric sample is removed and the bridge is rebalanced. The parallel capacitance C_P of the sample is the difference of the two readings of the standard capacitor. In resonance circuits, the sample is placed in the sample holder and the circuit is adjusted to obtain resonance. Then the sample is removed and the circuit is readjusted to get resonance. As dielectric constant is the measure of amount of charges that can be held by the dielectric material (capacitance), the relative dielectric constants are obtained by either method using the following equation:

$$\varepsilon` = C/C_o \tag{12}$$

where,

C = capacitance of the material (F)

C_o= capacitance of the air (F)



(a)

(b)

Figure 1. (a) Schering (capacitance) bridge, (b) resonant circuit.

Dielectric properties of grain samples were determined from measurements with a precision bridge at frequencies from 250 Hz to 20 kHz with samples confined in a coaxial sample holder (Corcoran et al. 1970). At very low frequencies, attention must be paid to electrode polarization phenomena which can invalidate the measurement data, and the frequency below which electrode polarization affects measurements depends on the nature and conductivity of the materials being measured (Foster and Schwan 1989; Kuang and Nelson 1998).

Q-meter based series resonant circuit techniques were used to obtain the dielectric properties data in the 1 to 50 MHz range for grain and seed samples (Nelson et al. 1953; Nelson 1965; 1973a; 1979; 1991). For 50 to 250 MHz range, RX meter was used with coaxial sample holders modeled as transmission line sections (Jorgensen et al. 1970). For the 200 to 500 MHz range, an admittance meter was used instead of the RX meter (Stetson and Nelson 1970). A technique was developed for measurements from 100 kHz to 1 GHz with two impedance analyzers (Lawrence et al. 1989). Bussey (1980) and Jones et al. (1978) used shielded coaxial sample holder for determining dielectric properties of grain with high frequency bridge measurements from 1 to 200 MHz.

For the radio frequencies, a material can be modeled electrically at any given frequency as a series or parallel equivalent circuit. From the radio frequency circuit parameter, the impedance or dielectric properties of that material at that particular frequency can be determined.

3.3. Measurements at high frequencies

Principles and techniques of dielectric properties measurements at microwave frequencies have been discussed in several reviews (Westphal 1954; Altschuler 1963; Redheffer 1964; Bussey 1967; Franceschetti 1967; Baker-Jarvis 1990). Dielectric properties measurement techniques can be categorized as reflection or transmission type techniques. Open or closed structures of resonant or non-resonant systems can be used for measuring the dielectric properties using these techniques (Kraszewski 1980). In principle, dielectric properties measurement at high frequencies (>100 MHz) can be done in three different ways namely, perturbation, transmission, and reflection methods.

3.3.1. Perturbation technique

In perturbation technique, the incremental changes in the resonant frequency and Q-factor (ratio of energy stored to energy dissipated) of a resonant cavity due to insertion of a very small sample of the material are measured. The sample of the material under test should be homogeneous. This technique is frequently used for its accuracy and high temperature capability (Sucher and Fox 1963; Bengtsson and Risman 1971; Metaxas and Meredith 1983). This technique is also used for measuring dielectric properties of low loss materials (Kent and Kress-Rogers 1986). The measurement is made by placing a sample completely through the center of a waveguide that has been made into a cavity. Changes in resonant frequency due to insertion of the sample are used to calculate the dielectric constant of the sample. Changes in the Q-factor are used to calculate the dielectric loss factor. Engelder and Buffler (1991) used a vector network analyzer to automatically display the changes in frequency. American Society of Testing and

Materials (ASTM 2001) published a standard procedure to design the resonant cavity. The size of the cavity depends on the frequency at which the measurement should be done. The size of cavity is inversely proportional to the frequency (a smaller cavity for a higher frequency).

3.3.2. Transmission techniques

Transmission techniques may be classified into two groups, namely guided transmission line techniques and free space transmission technique depending on whether the applicator used is a coaxial line or a waveguide or a pair of horn or lens antennas with test material in between.

Dielectric properties of a material can be determined by measuring the attenuation and phase shift of an electromagnetic signal which transmitted through a sample placed against the end of a short-circuited transmission line, such as a waveguide or a coaxial line or placed in between a pair of horn or lens antennas. A network analyzer analyzes the magnitudes and the phases of the transmitted and reference signals to produce the transmission coefficient, which is used to calculate the permittivity.

Transmission line technique. A sample of material is placed inside an enclosed transmission line to measure both reflection and transmission characteristics. This method is more accurate and sensitive than the more recent coaxial probe method but has the limitation in frequency range. It can be used at a narrower range of frequencies. When such methods are used to determine the moisture content, the frequency should be above 5 GHz to avoid the influence of ionic conductivity and bound water relaxation (Kraszewski 1996). However, the size of microwave components is usually proportional to the wavelength and therefore inversely proportional to frequency. As the substance must fill the cross-section of the transmission line (coaxial or rectangular), sample preparation is also more difficult and time consuming (Engelder and Buffler 1991; HP 1992). The thickness of the sample is chosen to be one quarter of the wavelength of the electromagnetic energy applied.

The waveguide method requires somewhat large sample size compared to the coaxial line technique. Dielectric properties of liquids and semi-solid type foods can be measured with this method by using a sample holder at the end of a vertical transmission line. Sample holder design is an important aspect of the measurement technique for determining dielectric properties of a specific material (Nelson 1999). A coaxial sample holder designed to accommodate flowing grain, to provide dielectric properties of grain over the range from 25 to 350 MHz was reported by Lawrence et al. (1998). Several measurement systems were developed using rectangular and coaxial-line sample holders for measuring dielectric properties of grain, seed, and fruit and vegetable tissue samples at frequency range from 1 to 22 GHz. (Nelson 1973a; 1983; 1984; 1991). Nelson (1983) used the same sample holders for measuring dielectric properties of coal and mineral samples (Nelson 1983). Dielectric properties of biscuit dough at 27 MHz were reported by Kim et al. (1998). The dielectric properties can be easily and inexpensively obtained by the transmission line technique, particularly if one utilizes a slotted line and standing-wave indicator (Nelson et al. 1974). A more sophisticated implementation of the technique utilizes a swept-frequency network analyzer, where the impedance is measured automatically as a function of frequency.

Dielectric properties of a material also can be determined using a partly or completely filled microwave resonator. Calibration of the resonator can be done by measuring dielectric properties of materials, whose dielectric properties are already reported (water, methanol, ethanol, etc.). Resonators can be used in the frequency range from 50 MHz to more than 100 GHz. In the case of a waveguide, resonators are not necessary to measure the dielectric properties. All materials except gases and some low-loss materials can be measured using this technique. There are, however, problems such as machining the sample to fit in the waveguide, with the sample preparation of solid materials. The accuracy is low compared to the transmission line technique with a resonator.

Microstrip transmission line technique. A microstrip employs a flat strip conductor suspended over a grounded plane using a low loss dielectric material. The effective permittivity (combination of the substrate permittivity and the permittivity of the material above the line) is dependent on the permittivity of the region above line. Keam and Holmes (1995) reported that the dielectric properties of a material can be determined by measuring the effective permittivity of a microstrip line covered by the material of interest.

Free-space transmission technique. This technique is non-destructive and contact-less. Because of this feature, this technique is particularly suitable for dielectric properties measurement at high and low temperatures (Akay et al. 2001). This technique can be used for a wide range of frequencies with good accuracy. The sample preparation is also simple as it is not necessary to machine the sample to fit in any microwave component. And this technique is easy to implement in industrial applications for continuous monitoring and control (Kraszewski 1980; 1996).

In the free-space transmission technique, a sample is placed between two antennas, one of those will transmit the energy and the other will receive the energy (refer to Figure 3 on page 36). Dielectric properties of the sample are determined by measuring the attenuation and phase shift of the signal. In most systems, the accuracy of dielectric properties determined depends mainly on the performance of the measuring system and validity of the equation used for the calculation. The usual assumption made while using this technique is that a uniform plane wave is normally incident on the flat surface of a homogeneous material, and that the planar sample has infinite extent laterally, so that diffraction effects at the edges of the sample can be neglected. Special attention should be paid to the choice of antennas, design of the sample holder and its location between the antennas.

3.3.3. Reflection techniques

Open ended coaxial probe technique. Stuchly and Stuchly (1980) reported that determination of the reflection coefficient at the sensor discontinuity plane allows one to derive the dielectric properties of a liquid or semi-solid sample terminating the coaxial line. This pioneered the development of open-ended coaxial probe. Probes with flat flanges may be utilized for measuring dielectric properties of solid samples (HP 1992). The dielectric properties were extracted from the reflection coefficient by modeling the fringing fields at the discontinuity as an equivalent lumped admittance (Stuchly et a1. 1974, Stuchly et a1. 1982). The equivalent circuit parameters were inferred by measuring the dielectric properties of a known material and using this to calculate the dielectric properties of an unknown material. A frequent assumption of this approach has been that the fringing fields in the sample produce a capacitance that is linearly proportional to sample relative permittivity and independent of both frequency and sample loss. This simple approach can produce significant errors that are functions of complex permittivity and that are thus, for unknown materials, difficult to quantify (Grant et al. 1989). They also explained the two basic approaches to determine the dielectric properties of a material using coaxial line open-circuit reflection coefficient (Grant et al. 1989):

1. methods that have used a lumped equivalent circuit description of the sensor's fringing fields;
2. methods that attempt a rigorous solution of the electromagnetic field equations appropriate for a coaxial line open to a dielectric sample.

Care must be exercised with this technique because errors introduced at very low frequencies and high frequencies, as well as for materials with low values of dielectric constant and loss factor. The technique is subject to errors if there are significant variations in the material or if there are air gaps or air bubbles between the end of the coaxial probe and the sample, and the technique is not suitable for determining permittivity of very low loss materials (Nelson and Bartley 1997). This technique is valid for 915 MHz and 2.45 GHz, for materials with loss factors greater than 1 (Sheen and Woodhead 1999; HP 1992). Interpretation for lower-loss materials such as fats and oils must be treated with caution. Typical open-ended probes utilize a 3.5 mm diameter coaxial line. The open-ended probe technique has been successfully commercialized and software and hardware are available. Open-ended coaxial line probes have been used successfully for convenient broadband permittivity measurements (Grant et al. 1989; Blackham and Pollard 1997) on liquid and semisolid materials of relatively high loss, which includes most food materials. This technique has been used for permittivity measurements on fresh fruits and vegetables (Tran et al. 1984; Nelson et al. 1994a; 1994b; 1995). Wang et al. (2003) measured the dielectric properties of insects over a frequency range from 1 MHz to 1.8 GHz. They also indicated that it is highly desirable to measure dielectric properties of biomaterials over the temperature range commonly experienced in insect controls, as thermal treatments for controlling insects in fruits were 20 to 60°C. The coaxial probe method is basically a modification of the transmission line method. It uses a coaxial line, which has a tip that senses the signal reflected from the material. The tip is brought into contact with the substance by touching the probe to a flat face of a solid or by immersing it in a liquid. While the method is quite easy to use and it is possible to measure the dielectric properties over a wide range of frequencies (20 MHz to 110 GHz), it is of limited accuracy particularly for materials with low values of dielectric constant and loss factor (Engelder and Buffler 1991; HP 1992). There has been a number of variations of the basic coaxial-line probe, e.g., elliptical ended (Xu et al. 1992) and conical tipped (Keam and Holdem 1997). Dielectric properties of six fruit commodities and associated insect pests have been measured between 1 MHz to 1.8 GHz using an open-ended coaxial probe technique at temperatures between 20 and 60°C (Wang et al. 2003).

TDR (reflectometry method). This method also utilizes the reflection characteristics of the material to determine the dielectric properties. The measurement is very rapid and accuracy is high, with a few percent of error (Afsar et al. 1986). The sample size is very small and the material under test must be homogeneous. Although these methods are expensive, they are excellent tools for advanced research on the interaction of the electromagnetic energy and materials over a wide frequency range (Mashimo et al. 1987; Ohlsson et al. 1974). The dielectric properties of honey-water mixture have been investigated and tabulated using the time domain reflectometry (TDR) technique in the frequency range of 10 MHz to 10 GHz at 25°C by Puranik et al. (1991).

Six - port reflectometer using an open-ended coaxial probe. Ghannouchi and Bosisio (1989) worked on non-destructive broadband permittivity measurements using open-ended coaxial lines as impedance sensors, which are of great interest in a wide variety of biomedical applications. An attempt was made to replace expensive automatic network analyzer (ANA) by combining the capabilities of personal computers with customized software to derive all the necessary information from less expensive components. The reported measuring system consists of a microwave junction designed to operate from 2 to 8 GHz and a number of standard microwave laboratory instruments (power meters, counters, sweepers, etc.) controlled by an IEEE 488 bus interface by a microcomputer to provide a precision low-cost automatic reflectometer suitable for permittivity measurements. The device under test is an open-ended coaxial test probe immersed in the test liquid kept at a constant temperature. Data acquisition and reduction are fully automatic. The complex reflection coefficient is calculated from the four power readings and the calibration parameters of the six-port reflectometer.

It is concluded that the six-port reflectometer can provide non-destructive broadband permittivity measurements with an accuracy comparable to commercial ANA accuracy but at a considerable reduction in equipment costs. This effective transmission line method, used to represent fringing fields in the test medium, provided a good model to interpret microwave permittivity measurements in dielectric liquids. Using such a model, the precision on relatively high-loss dielectric liquid measurements is expected to be good. However, this method involves a more complex mathematical procedure in order to translate the signal characteristics into useful permittivity data.

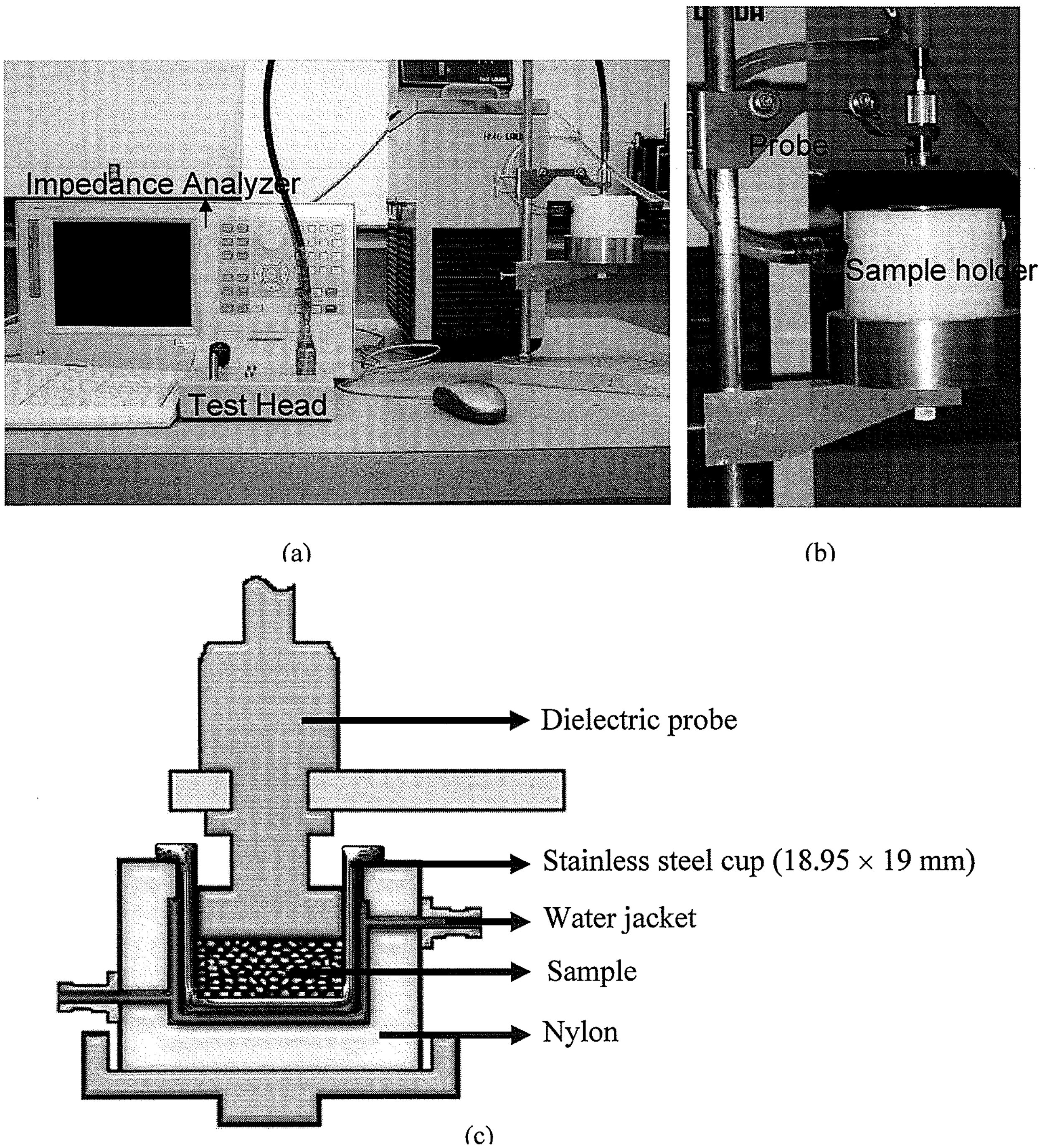
4. MATERIALS AND METHODS

4.1. Sample preparation

Hard red spring (HRS), (AC Barrie) wheat was obtained from the 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 for 1 h to bring the moisture content to 14% (wet mass basis). After mixing, 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 during the day to ensure a uniform distribution of moisture. Moisture contents of the wheat samples were determined by drying triplicate samples of 10 g at 130°C for 19 h (ASAE 1997).

4.2. Open-ended coaxial probe method (Reflection technique)

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 mounted in a Delrin water jacket with an O-ring seal (Figure 2). 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 through 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.



(a) (b) (c)

Figure 2. (a) Coaxial probe measurement setup, (b) Sample holder and probe, and (c) Cross sectional view of sample holder.

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). The open-ended coaxial probe was connected to the impedance analyzer using a coaxial cable. A general purpose interface board (GPIB) was used to connect the impedance analyzer to the computer. The experimental setup is shown in Figure 2.

Any measuring instrument, however sophisticated it may be, has a certain degree of error in actual use. The measured value is always a combination of actual value plus the systematic measurement errors. Therefore, before starting the dielectric properties measurements, the impedance analyzer was calibrated by measuring the reflection coefficients of three standards (open, short, and standard load (distilled water)) one by one to the test head port of the impedance analyzer. To decrease the low-loss coefficient above the frequency band near 1 GHz, which is difficult to decrease by only using open-short-load calibration, a low-loss capacitor measurement was added to the calibration procedure. The bulk wheat sample (150 kernels) was filled into the sample cup, and the sample cup and water jacket assembly were raised with supporting platform for the probe to enter the sample cup and make firm contact with the sample. Dielectric properties measurements were then performed at 24°C. Fifty replications were done using this method. For each replicate, the same sample was emptied and refilled again.

With the impedance analyzer, software provided by Agilent (Santa Clara, CA) was used to convert the measured complex reflection coefficients to complex dielectric properties. In the case of the vector network analyzer, the experimental setup was the same as for the impedance analyzer measurements, but instead of the impedance analyzer, the open-ended coaxial probe was connected to a vector network analyzer (Anritsu 360B, Anritsu, Ottawa, ON). The dielectric properties of bulk wheat samples were measured over the frequency range from 0.04 GHz to 3 GHz at 24°C. Before measuring the complex scattering reflection coefficients (S_{11}), the analyzer was calibrated by the reflection only (1-port) calibration method. A vector network analyzer should be calibrated for twelve errors which can be grouped into four namely, internal system errors, random errors, transmission measurement errors and reflection measurement errors. The errors are:

a. Internal errors

1. Radio frequency (RF) leakage;
2. Intermediate frequency (IF) leakage;
3. System interaction.

b. Random errors

1. Frequency;
2. Repeatability;
3. Noise;
4. Connector repeatability;
5. Temperature and other environment factors;
6. Calibration variables.

c. Transmission measurement errors

1. Source match;

2. Load match;

3. Tracking.

d. Reflection measurement errors

1. Source match;

2. Directivity;

3. Tracking.

The reflection only calibration method was used to reduce both internal and reflection measurement errors. Transmission errors are not applicable and random errors are part of any measurement. Then the S_{11} parameters of air (S_{o11}), short circuit (S_{s11}), and distilled water (S_{w11}) were measured. Thirty replications were done using this method. The following equation was used to convert the S_{11} parameters to dielectric properties (Kato et al. 2004).

$$\varepsilon_m = \frac{\varepsilon_w (S_{m11} - S_{o11})(S_{s11} - S_{w11}) + (S_{m11} - S_{w11})(S_{o11} - S_{s11})}{(S_{m11} - S_{s11})(S_{o11} - S_{w11})} \quad (13)$$

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.

4.3. Free space method (Transmission technique)

The dielectric properties of bulk wheat samples were measured over the frequency range from 1 GHz to 2 GHz at 24°C using the 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. Styrofoam has unit dielectric constant and negligible loss factor value, so it does not affect the measurements (Trabelsi and Nelson 2003).

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 3.

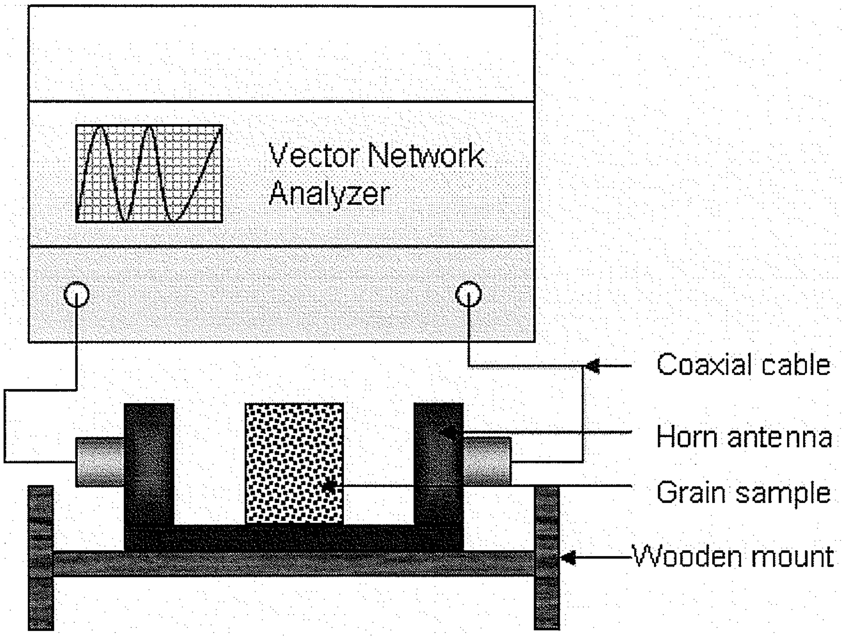


Figure 3. Free space method measurement setup.

Before starting the measurements, the vector network analyzer was calibrated by 1-path, 2-port calibration method. The 1-path 2-port calibration method was used to reduce both internal errors and transmission measurement errors of the vector network analyzer. 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 bulk wheat sample were calculated. Thirty replications were done using this method. The dielectric constant and loss factor values were computed from the transmission coefficients of the sample using the following equations (Trabelsi and Nelson 2003):

$$\varepsilon' = \left(1 + \frac{\phi \lambda_0}{360d}\right)^2 \tag{14}$$

$$\varepsilon'' = \frac{A\lambda_0}{8.686\pi.}\sqrt{\varepsilon'} \tag{15}$$

where,

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

λ_0 = wavelength at free space (m)

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

d = thickness of the sample (m)

φ = phase of transmitted wave (degrees).

The integer n was computed by performing measurements at two frequencies (f_1, f_2) (Trabelsi et al. 2000). The following assumptions were made during the calculation of n.

$$\lambda_1(\varphi_1 - 360n_1) = \lambda_2(\varphi 2 - 360n_2) \tag{16}$$

$$n_2 = n_1 = n \tag{17}$$

Therefore,

$$n = \frac{\lambda_1\varphi_1 - \lambda_2\varphi_2}{360(\lambda_1 - \lambda_2)} \tag{18}$$

The dielectric constant and loss factor calculated with equations (14) and (15) were the average values for the entire sample, assuming the physical properties are the same throughout the sample.

5. RESULTS AND DISCUSSIONS

5.1. Coaxial probe method

Four of the 50 replications which were done using coaxial probe with the impedance analyzer are presented in Figures 4 and 5 where the frequency dependence of the measured dielectric constant and dielectric loss factor (relative permittivity) are shown. The dielectric properties were calculated from the reflection coefficients measured by the impedance analyzer using the software provided by Agilent (85070, Agilent, Santa Clara, CA). From the published literature (Trabelsi and Nelson 2003), it was expected that the dielectric constant of the bulk wheat samples should decrease with

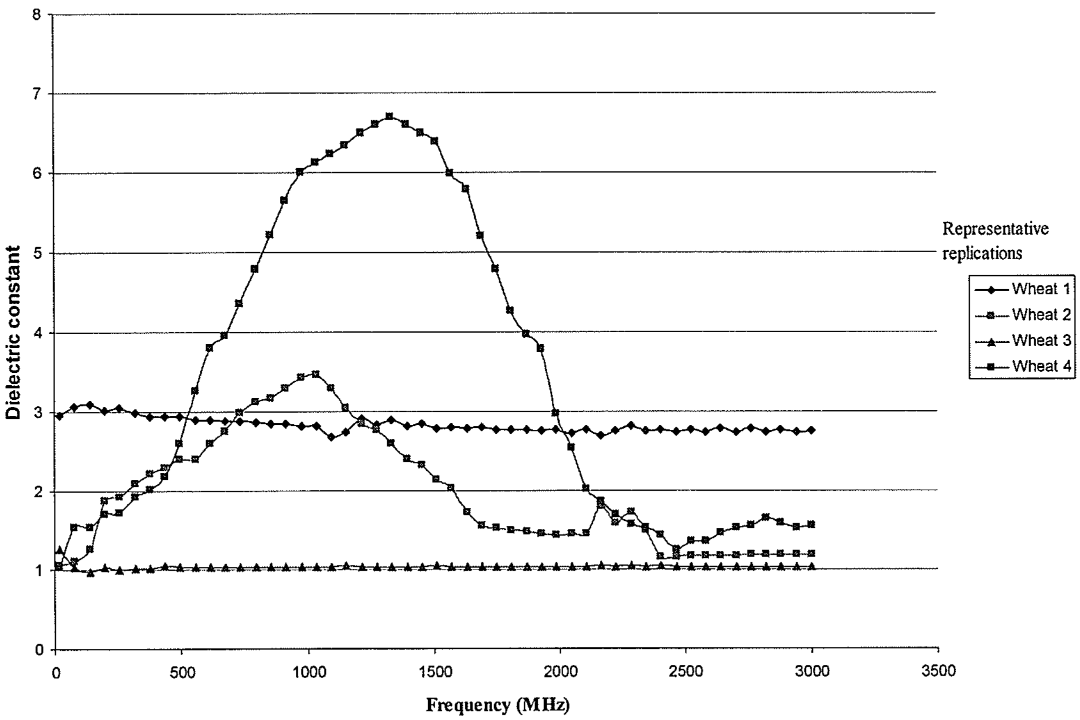


Figure 4. Dielectric constant of bulk wheat sample (coaxial probe – impedance analyzer method).

an increase in frequency and the loss factor should increase or decrease with an 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

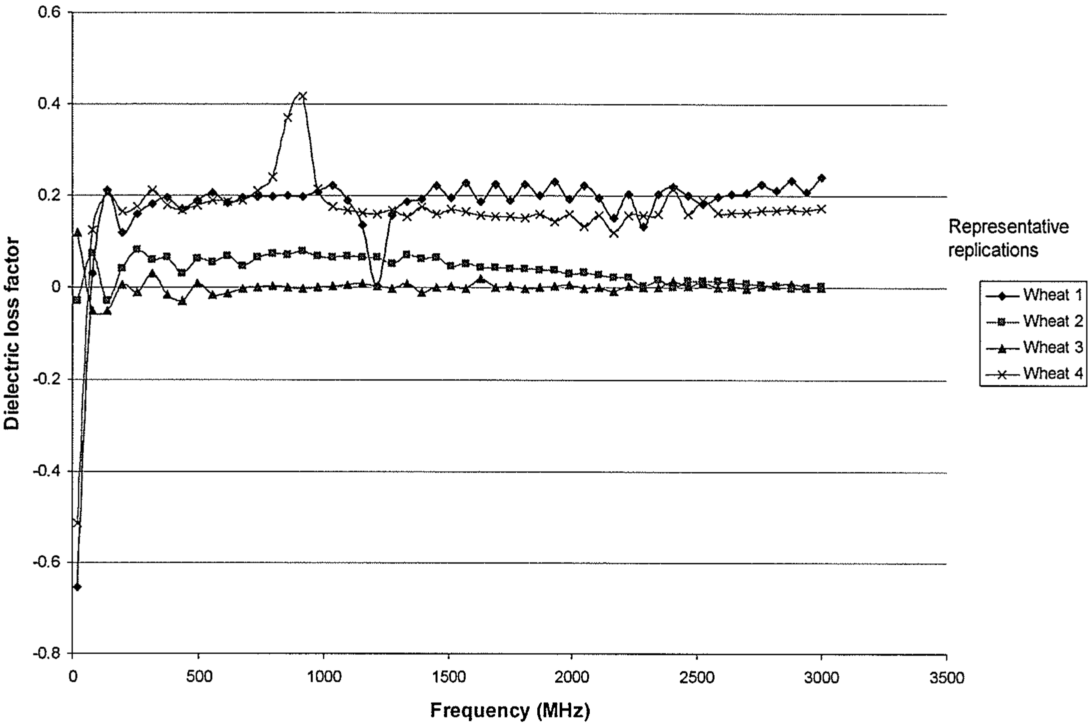


Figure 5. Dielectric loss factor of bulk wheat sample (coaxial probe - impedance analyzer method).

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. When water was used as a sample such variability was not noticed because of a good contact between the probe and liquid water (Figure 6 and 7).

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. If the area of air gaps contacted with the probe exceeds the aperture area of the probe, the probe could not measure the dielectric properties properly. Problems of resonance due to reflections from the dielectric interfaces at the sample and sample cup boundaries may also have caused this variability.

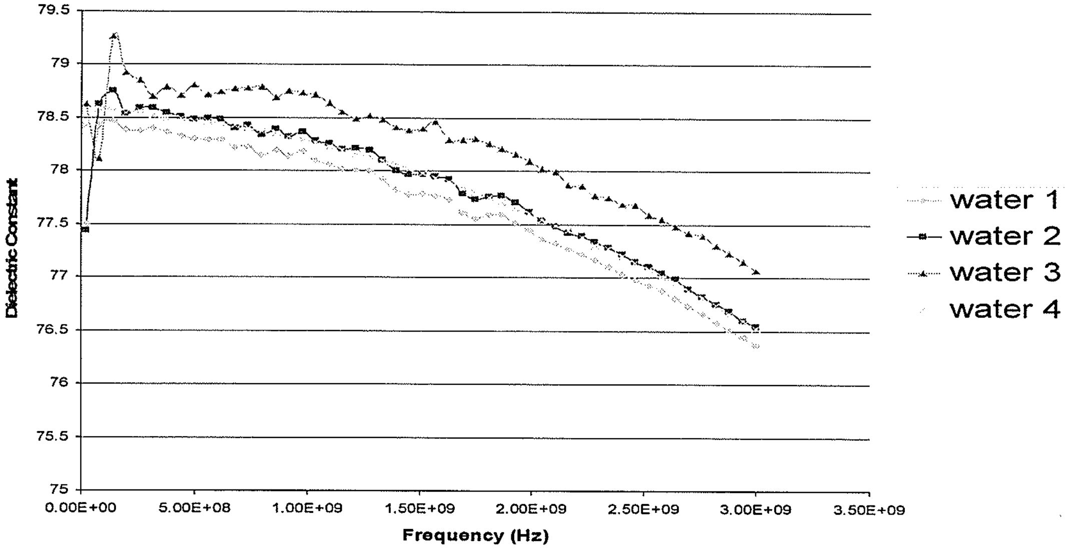


Figure 6. Dielectric constant of distilled water (coaxial probe - impedance analyzer method).

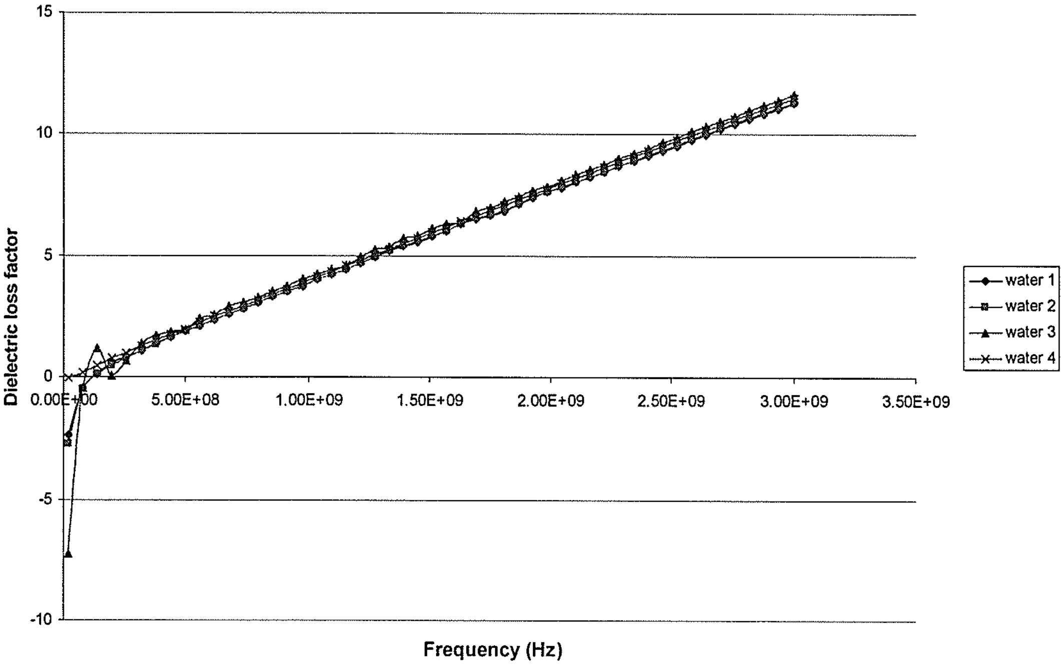


Figure 7. Dielectric loss factor of distilled water (coaxial probe - impedance analyzer method).

Effect of gaps on permittivity measurement using the coaxial probe can be best explained using a Westphal (1950) capacitor model. In a homogeneous coaxial line, the inductance per unit length (L) is:

$$L = \frac{1}{2\pi \ln\left(\frac{r_o}{r_i}\right)} \tag{19}$$

where,

r_o = inner radius of the coaxial line (m)

r_i = outer radius of the coaxial line (m)

and the capacitance per unit length is (C):

$$C = \frac{2\pi\varepsilon_r}{\ln\left(\frac{r_o}{r_i}\right)} \tag{20}$$

where,

ε_r = permittivity (F/m)

When a single gap of permittivity ε_{rg} is introduced into the system, and the inner and outer radius of the sample having permittivity ε_{rs} are r_{is} and r_{os}, respectively, then the capacitance of the gap in coaxial system and the capacitance of sample are:

$$C_{gap} = \frac{2\pi\varepsilon_{rg}}{L_1} \tag{21}$$

$$C_{sample} = \frac{2\pi\varepsilon_{rs}}{L_2} \tag{22}$$

where,

$$L_1 = \ln\left(\frac{r_o}{r_i}\right) - \ln\left(\frac{r_{os}}{r_{is}}\right) \tag{23}$$

$$L_2 = \ln\left(\frac{r_{os}}{r_{is}}\right) \tag{24}$$

Therefore, the observed capacitance of the whole system would be:

$$C_o = \frac{2\pi\varepsilon_{ro}}{L_3} \tag{25}$$

where,

$$L_3 = \ln\left(\frac{r_o}{r_i}\right) \tag{26}$$

Observed capacitance (C_o) of the whole system as a function of capacitance of gap and sample is:

$$C_o = \frac{C_{gap} C_{sample}}{C_{gap} + C_{sample}} \tag{27}$$

This model neglects the junction capacitance at the boundary between the sample section and the transmission line. Observed permittivity (ε_{ro}) can be written as a function of gap permittivity (ε_{rg}) and true sample permittivity (ε_{rs}).

$$\varepsilon_{ro} = \frac{\varepsilon_{rs}\varepsilon_{rg} L_3}{\varepsilon_{rs} L_1 + \varepsilon_{rg} L_2} \tag{28}$$

This equation explains the effect of gap between a sample and the contact surface of the probe in the complex dielectric properties measurement using the coaxial probe. In the numerator part of Eq. 28 the gap permittivity is in multiplication with the sample permittivity and inductance of the whole coaxial system but in the denominator part it is just multiplied with the inductance of the sample alone so an increase in gap permittivity will lead to an increase in observed permittivity.

When the vector network analyzer was used instead of the impedance analyzer the obtained dielectric constant and dielectric loss factor values were absolutely equal to that of open air. Ten of the thirty replications are presented in Figure 8 and 9.

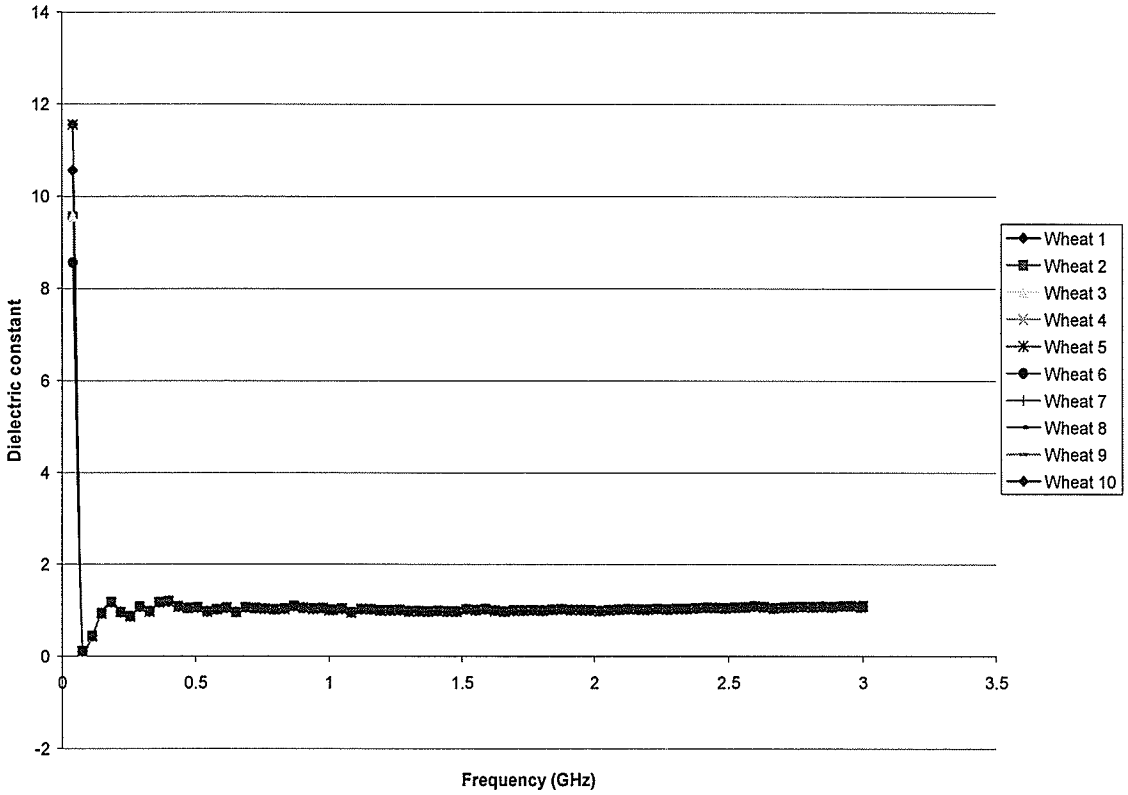


Figure 8. Dielectric constant of bulk wheat sample (coaxial probe – vector network analyzer method).

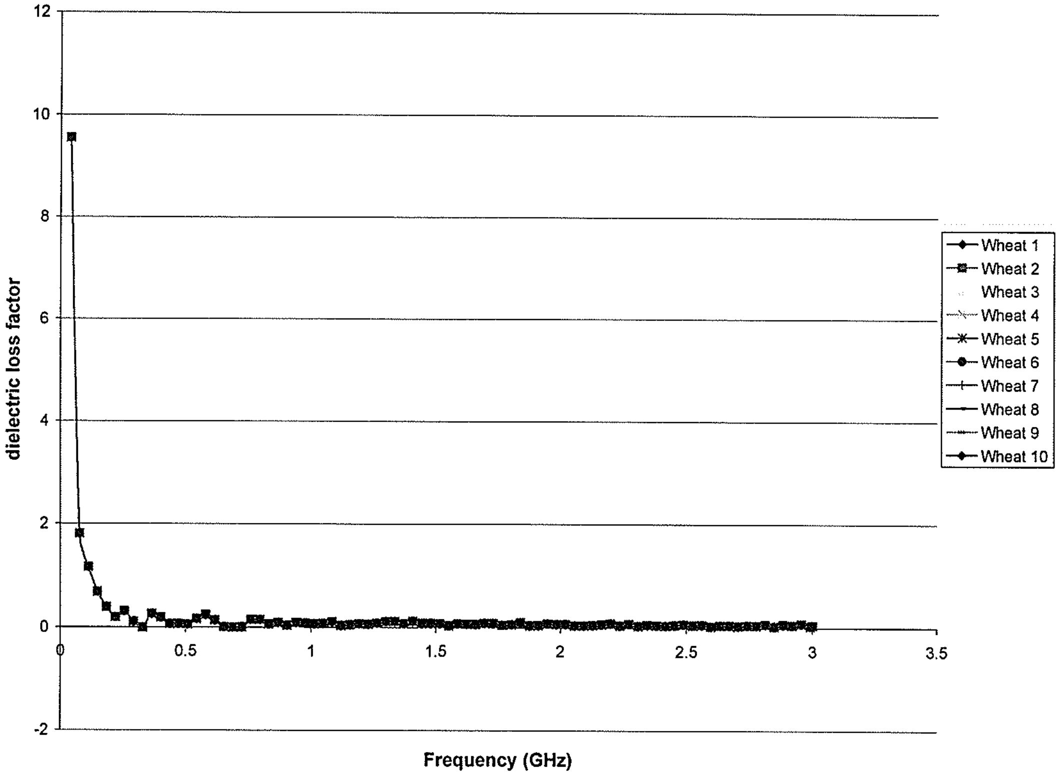


Figure 9. Dielectric loss factor of bulk wheat sample (coaxial probe – vector network analyzer method).

The results obtained were very consistent but when the area of air gaps exceed the aperture area of the open-ended coaxial probe, the network analyzer could not find the difference in S_{11} parameters of open air and bulk wheat samples. Therefore, the dielectric properties calculated from the S_{11} parameters measured by the network analyzer are the same as the dielectric properties of open air.

5.2. Free space method

Results of the dielectric properties (relative permittivity) measurements at various thicknesses of a bulk wheat sample are presented in Figures 10 and 11. The results were consistent but it was expected that the dielectric constant of bulk wheat should decrease with an increase in frequency and ranging from 2 to 4 (Trabelsi and Nelson 2003), however, the results obtained showed an increase in dielectric constant with an increase in frequency. Also, there was a wavy trend in the dielectric constant, the values increased with the increase in frequency ranging from 0.65 to 0.95. That is because of the post

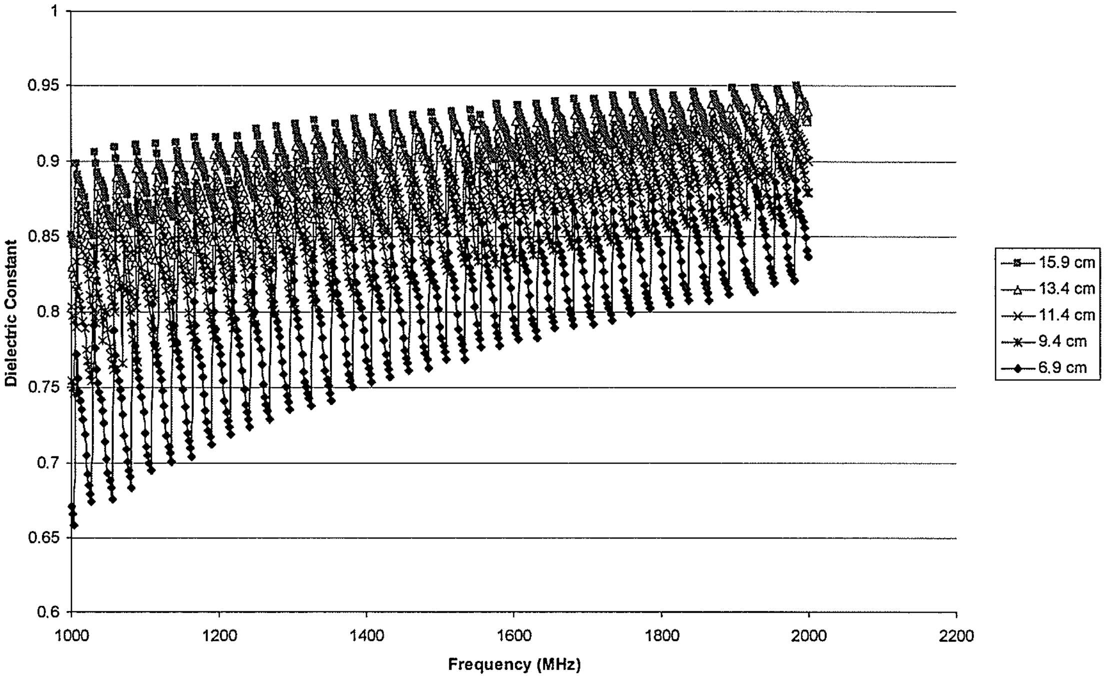


Figure 10. Dielectric constant of bulk wheat sample (free space method) at different thicknesses.

calibration mismatches and possible multiple path transmission (Trabelsi and Nelson 2003).

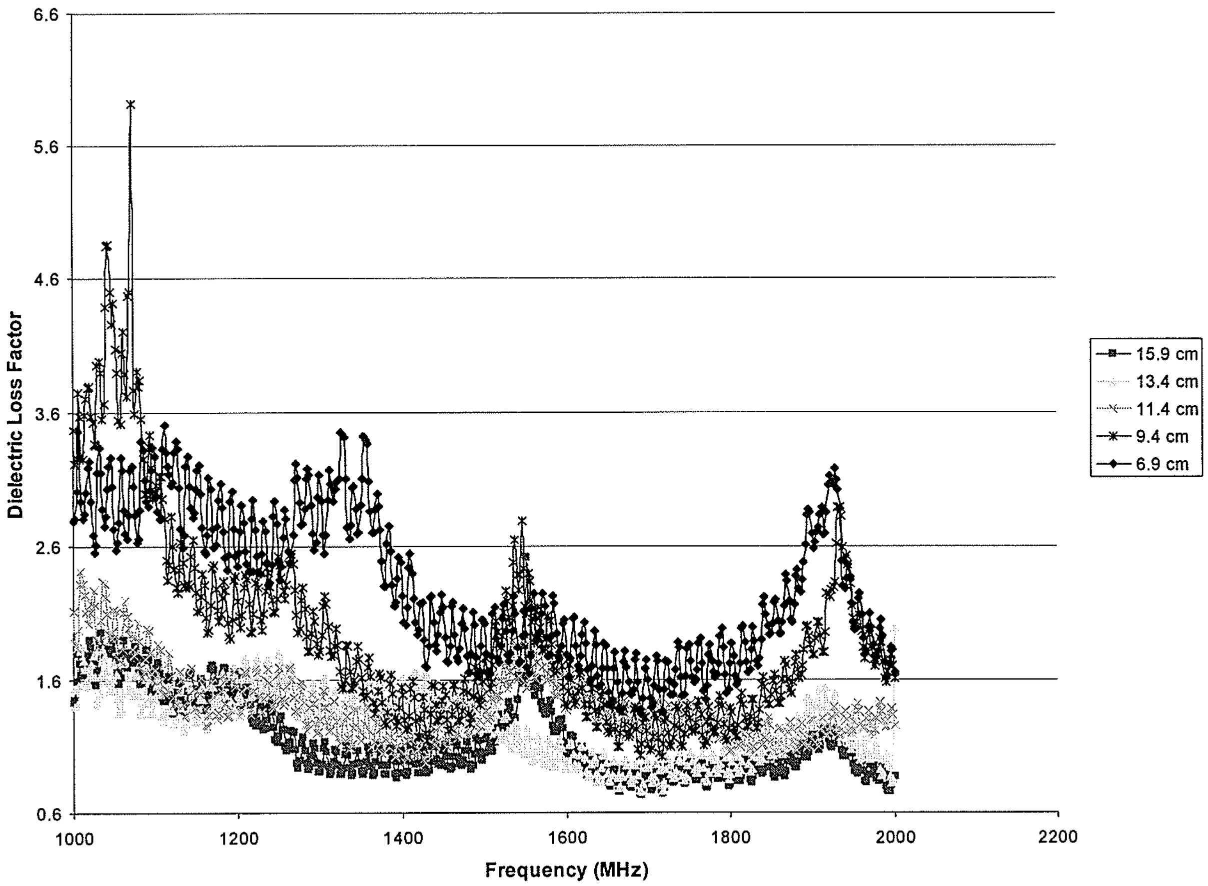


Figure 11. Dielectric loss factor of bulk wheat sample (free space method) at different thicknesses.

It was expected that the dielectric loss factor should range from 0.1 to 1 (Trabelsi and Nelson 2003). But the results indicate a noisy pattern ranging from 0.7 to 6. This noisy pattern may be due to the property of the channel. The channel is the link through which the signal travels. At any temperature above absolute zero, electrons in any material are in constant random motion. Because of the intrinsic randomness of that motion, however, there is no detectable current in any one direction. That is, electron flow in any single direction is cancelled over short time periods by equal flow in the opposite direction. Electron motions are therefore statistically de-correlated. There is, however, a continuous series of random current pulses generated in the material, and those pulses are the source of a noise signal.

Plots of attenuation and phase shift for the wheat sample of 6.9 cm thickness were shown in Figure 12 and 13. The noises in both attenuation and phase shift may because of the multiple reflections inside the sample. 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 (Trabelsi and Nelson 2003). 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. Lens antennas could be used with horn antennas or on their own so that the planar wave would be normally incident to the surface of the sample which would avoid the edge diffractions.

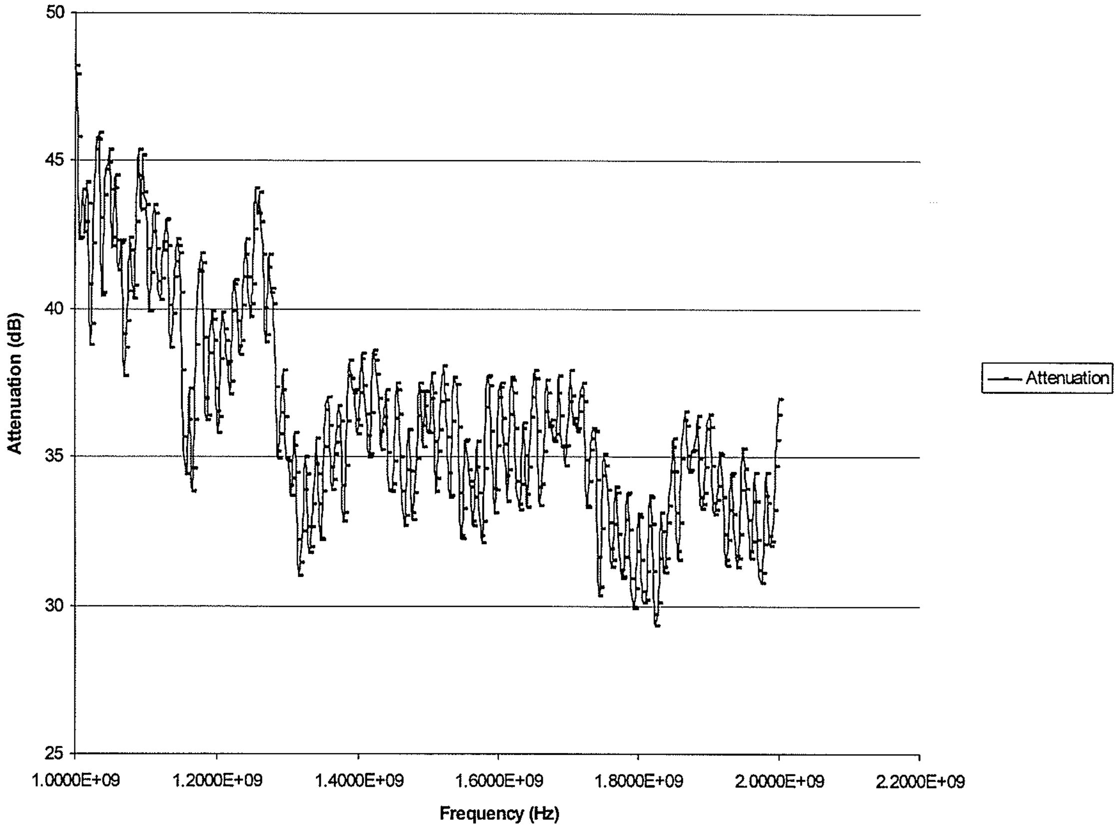


Figure 12. Attenuation of a 6.9 cm thickness bulk wheat sample (free space method)

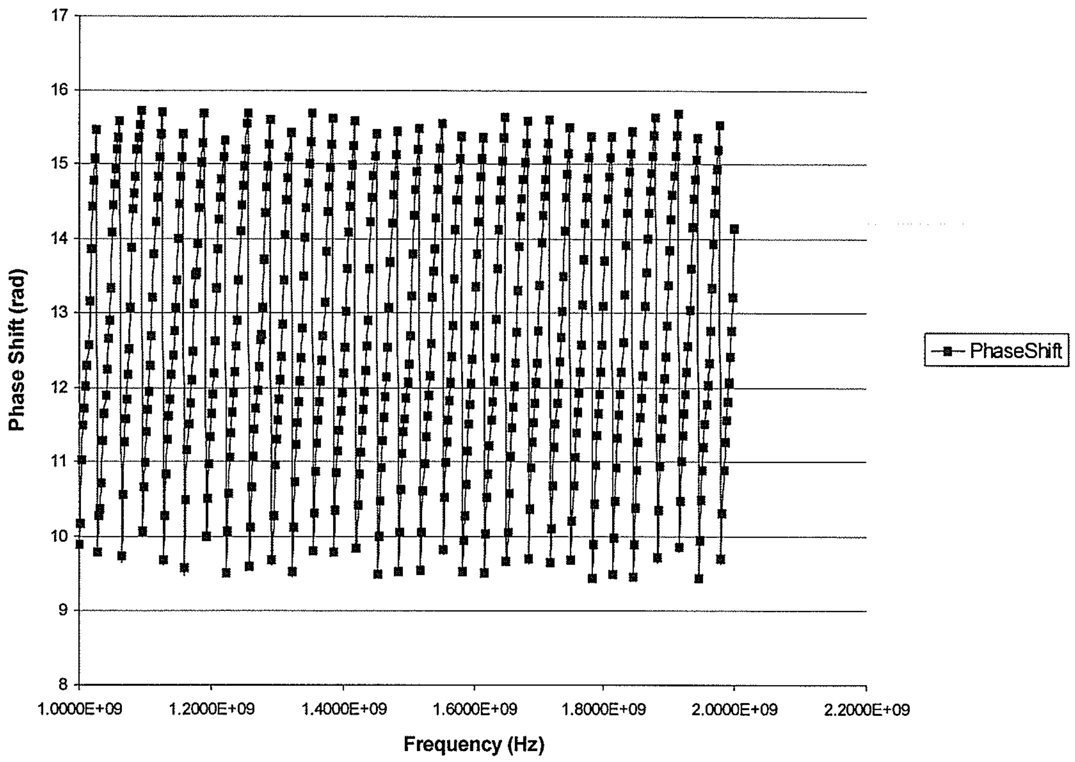


Figure 13. Phase shift of a 6.9 cm thickness bulk wheat sample (free space method)

5.3. Mixtures' model

The complex refractive index mixture equation (Eq. 10) can be used to estimate the dielectric properties of any solid materials from dielectric measurements on particulate samples of those same materials (Nelson 1991). Thus, the following equation was used to estimate the dielectric properties of wheat samples from the bulk wheat samples measurements.

$$\varepsilon_g = \left(\frac{\varepsilon^{1/2} + v_g - 1}{v_g} \right)^2 \qquad (29)$$

where,

ε_g = estimated dielectric properties of wheat samples

ε = observed dielectric properties of wheat samples

v_g=volume fraction occupied by wheat in bulk wheat samples.

The volume fraction occupied by wheat can be calculated from the bulk density and porosity of the bulk wheat samples. The calculated bulk density value of 0.797 g/cm^3 was used to estimate the dielectric properties from the observed values of coaxial probe method. For free space method, the calculated bulk density values of 0.774, 0.769, 0.771, 0.772, 0.769 g/cm^3 were used to estimate the dielectric properties for sample thicknesses of 15.9, 13.4, 11.4, 9.4, 6.9 cm, respectively. The porosity value 37.97% which was measured by a pycnometer was used for estimating dielectric properties from both methods.

Figure 14 and 15 shows the estimated dielectric constant and dielectric loss factor values obtained using the values measured by the coaxial probe method plotted against frequency.

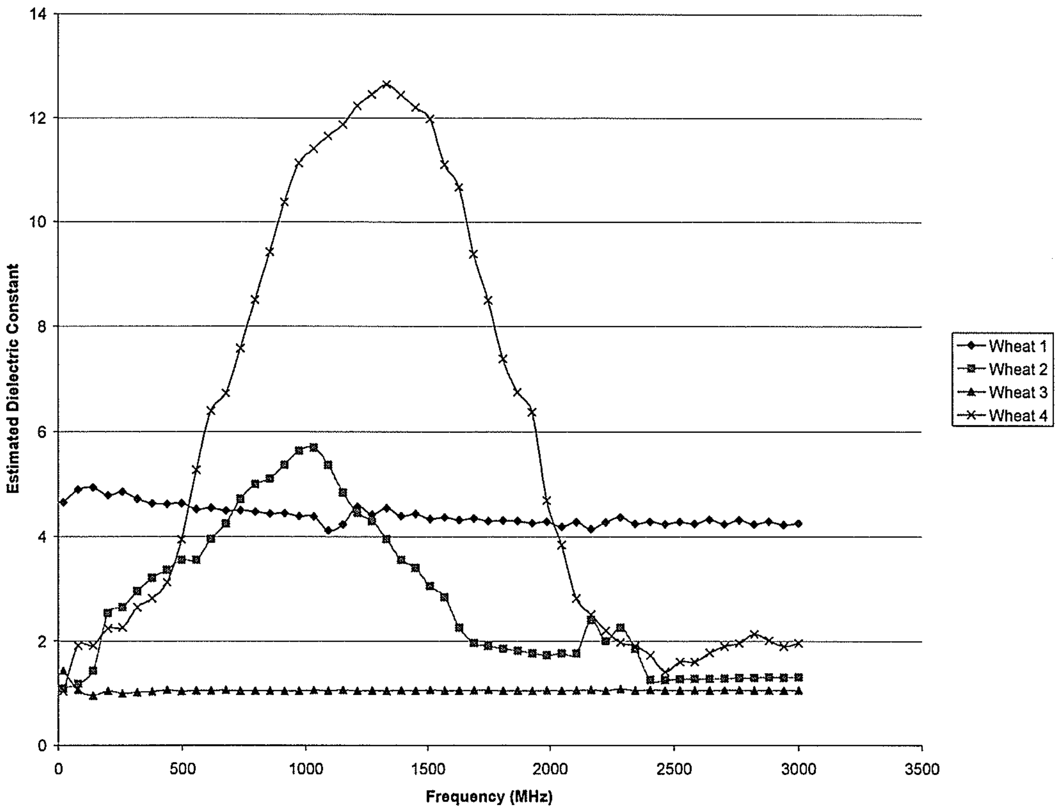


Figure 14. Dielectric constant values of wheat samples estimated using the complex refractive index mixture equation (coaxial probe method)

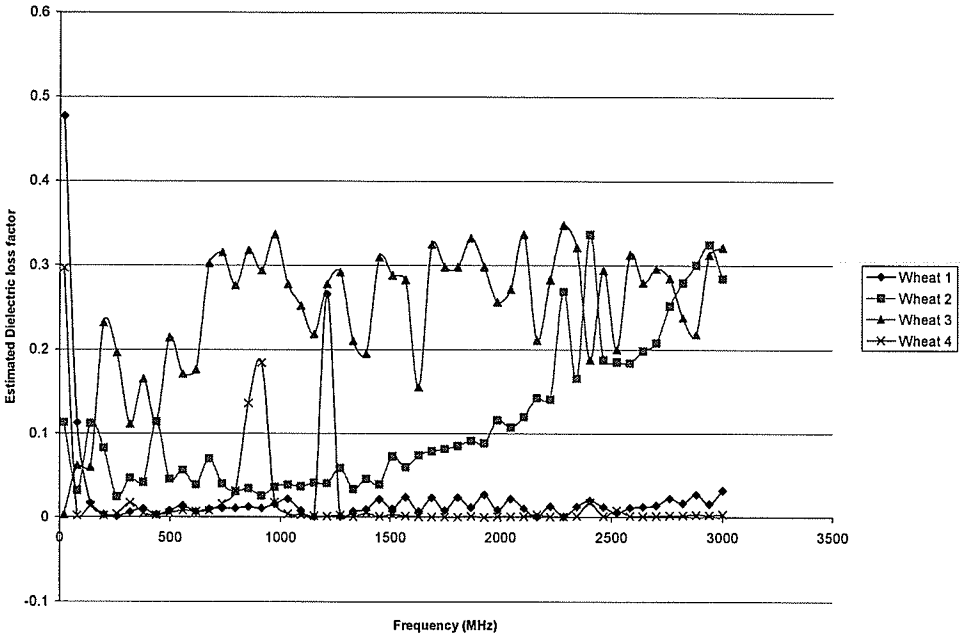


Figure 15. Dielectric loss factor values of wheat samples estimated using the complex refractive index mixture equation (coaxial probe method)

The values of dielectric constant and dielectric loss factor are ranging from 1 to 13 and the loss factor values are in the expected range (0 to 1). The estimated dielectric constant and dielectric loss factor values, estimated using the mixtures' model are also highly variable and the trend is inconsistent.

Figures 16 and 17 show the estimated dielectric constant and dielectric loss factor values obtained using the values measured by the free space method plotted against frequency.

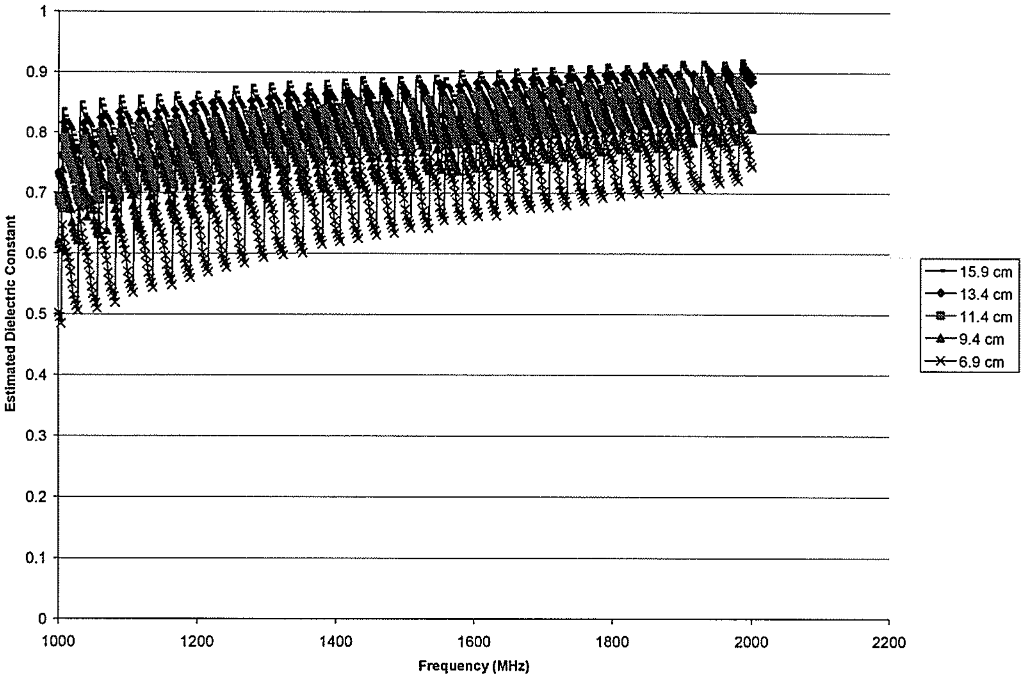


Figure 16. Dielectric constant values of wheat samples at different thicknesses estimated using the complex refractive index mixture equation (free space method)

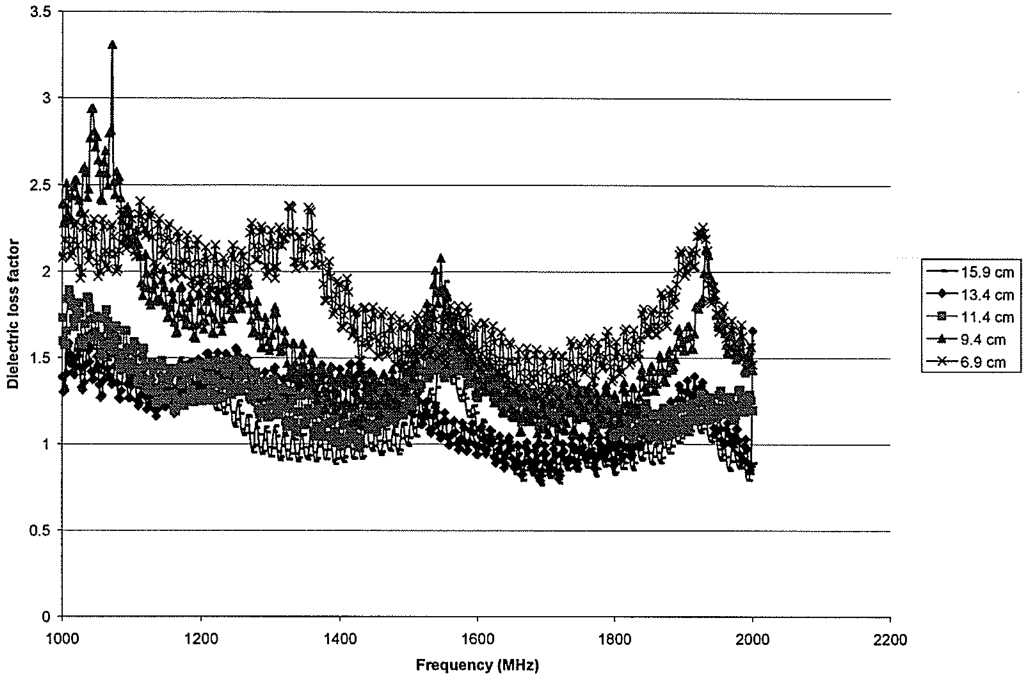


Figure 17. Dielectric loss factor values of wheat samples at different thicknesses estimated using the complex refractive index mixture equation (free space method)

The estimated dielectric constant and dielectric loss factor values obtained from the free space method measurements also show the saw tooth pattern caused by the post calibration mismatches and the multiple reflections occurring inside the sample. The estimated values of dielectric constant were ranged from 0.5 to 1 and the loss factor values ranged from 0.5 to 3.5, which were not equal to the expected values of 2 to 4 and 0.1 to 1 for dielectric constant and dielectric loss factor, respectively.

6. CONCLUSIONS

1. Air gaps in the bulk wheat sample severely limit the accurate measurements of dielectric properties by open-ended coaxial probe with the impedance analyzer and with the network analyzer (reflection technique) and horn antennas with the network analyzer (transmission technique).
2. An open-ended coaxial probe technique can only be used for homogeneous materials such as liquid foods.
3. Horn antennas alone did not succeed in measurement of dielectric properties of bulk wheat in the free space measurement technique.

7. FUTURE WORK

The open-ended coaxial probe should be custom built with larger flange area, so that the effective density would not affect the measurement of dielectric properties.

Further examination should be made of the feasibility of lens antennas in free space measurement technique for determining dielectric properties of bulk wheat samples.

Time domain gating could be applied in free space measurement technique for improving the measurement of the dielectric properties of bulk wheat samples.

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