April 2008 *Volume 2 Issue 1*

Trade Science Inc.

BioTechnology

An Indian Journal

FULL PAPER

BTAIJ, 2(1), 2008 [23-29]

An analytical approach to predicting moisture contents of spring barley kernels through microwave permittivity data

Zeeshan Ahmad[1], Ashutosh Prasad*[1], Kamlesh Prasad[2]

[1]University Dept. of Physics Tilkamanjhi Bhagalpur University, Bhagalpur- 812007, (INDIA)

[2]Dept. of Food Engineering and Technology, SLIET,Longowal Sangrur-148106, (INDIA)

E-mail : ashutosh_Pd_phy @ indiatimes.com

Pacs nos: 77.20-d; 77.84 Lf; 78.70 Gq; 81.40 Tv; 72.80 Tm

Received: 6th February, 2008 ; Accepted: 11th February, 2008

ABSTRACT

In the present paper, an attempt has been made at finding the moisture dependence of the relative permittivity and dielectric loss factor of Spring Barley kernel samples at 2.45 GHz and 24^{0}C to give quadratic and cubic models for the variation of the two dielectric properties with (i) decimal moisture content, m (ii) moisture density (product of decimal moisture content and bulk density of the sample, m_d) and (iii) moisture specific volume (ratio of decimal moisture content to bulk density of the sample m_v). The last parameter has been introduced by the authors in order to remove or minimize the irregularities in the trend of variation of dielectric loss factor with moisture content. Resulting data and the plots of such variations, derived from eight equations for the effective dielectric function of random media are presented. On their bases, it is shown that the moisture content of a given sample could instantly be estimated for a given set of values for the two dielectric properties and the technique may be applied over the entire acceptable range of moisture contents without the aid of any reference data points. A better performance of the present models compared with those of Nelson and Kraszewski is reported. Average percentage errors of prediction of about 1.4 and 1.5 from the present quadratic and cubic models for relative permittivity versus decimal moisture content have been achieved as compared to 3.61 and 3.5 from the corresponding Nelson's models. The average percentage errors in loss factor from the present models are about 0.4 and 0.5 as compared to 24.8 from the Nelson's solitary model.

KEYWORDS

Permittivity;
Dielectric loss factor;
Nonlinear regression;
Agricultural products;
Microwave frequency;
Composite materials.

INTRODUCTION

The use of electrical properties of grains for moisture measurement has been the most prominent agricultural application for dielectric properties data. The dielectric properties offer a potential means in making devices for sensing the moisture content of individual grain kernels, which help in preventing the spoilage of large blended lots stored in elevators, ships or mills[1-2].

Several efforts to model the dielectric properties of

FULL PAPER

grains have been made[3-4]. The purpose of the present paper is to consider a more general approach towards modeling the dielectric properties of samples of spring barley, *Hordeum Vulgares L.*, using the data of results for them at a fixed frequency of 2.45 GHz at 24^0C, to present empirical expressions which allow predictions of permittivity and loss factor.

The electrical properties of grains are influenced by ionic conductivities and bound-water- relaxations. The result of measured values is then a complicated function of the amount of water in the grain. However, all these effects disappear almost completely at higher microwave frequencies. Thus, microwaves offer a non-destructive, sensitive and feasible method for determining the water content in grains.

EXPERIMENTAL

Resulting data for measured values of bulk density, decimal moisture content (m) and dielectric constant were taken from the TABLE 5[5]. For deriving the values of bulk density ρ_b, Kernel densities ρ_k and hence the volume fractions (= ρ_b/ρ_k) of the material in the mixture, the equations (7) and (8) of the same paper[5] were used. The general quadratic and cubic models given by Nelson and Kraszewski[2] connecting dielectric constant, moisture contents and frequency of operation were used for their comparison with the corresponding new models proposed in the present study. The equations are:

$$\varepsilon' = [1+\{A_2 - B_2 \log f + (C_2 - D_2 \log f)\, M\}\, \rho]^2 \qquad (1)$$

$$\text{And } \varepsilon'' = [1+\{A_3 - B_3 \log f + (C_3 - D_3 \log f)\, M\}\rho]^3 \qquad (2)$$

The solitary equation for the dielectric loss factor available for comparison is of the form:

$$\varepsilon'' = 0.146\ \rho^2 + 0.004615\ M^2\rho^2[0.32\log f + 1.743/\log f - 1] \qquad (3)$$

where $\rho = \rho_b$ = bulk density of the material in gramxcm^{-3} , M = % moisture content, wet basis = 100 m, f = frequency of operation in MHz.

The values of constant viz., A_2, B_2, C_2, D_2 or A_3, B_3, C_3, and D_3 of equations (1) and (2) for spring barley were taken from the TABLE 6 of Nelson's paper[2].

Model development and evaluation of constants

Based on observations of almost linear plots obtained for the dependence of relative permittivity of grains and cereals with moisture content, especially in the microwave range, it was proposed to give quadratic as well as cubic models for such variations. On similar lines of the works of Noh and Nelson[6] on rice samples, the second and a new term, called moisture density (product of decimal moisture content and bulk density), was also used. The third and the new term, called moisture specific volume(ratio of decimal moisture content to bulk density, m_v), in addition to m and m_d, was also proposed to be incorporated in the composite model proposed in the present study. The composite models are:

Quadratic

$$\varepsilon' = a\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^2 + b\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix} + K_1 \qquad (4a)$$

and

$$\varepsilon'' = c\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^2 + d\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix} + K_2 \qquad (4b)$$

Cubic

$$\varepsilon'' = a\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^3 + b\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^2 + c\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix} + K_1 \qquad (5a)$$

and

$$\varepsilon'' = d\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^3 + e\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix}^2 + f\begin{vmatrix} m \\ m_d \\ m_v \end{vmatrix} + K_2 \qquad (5b)$$

The value of the constant K_1 was taken to be equal to the average of the relative permittivities as derived from equations (1) and (2) by putting M= O in them. The corresponding value of ρ was derived from equation (7) of the Nelson's paper[5] by putting m = O in it. Similarly, the value of K_2 was taken to be equal to the value of the loss factor from equation (3) of the present paper by putting the abovementioned value of ρ corresponding to M=0. In this way

$$K_2 = (\varepsilon'')_{m=0} = 0.146\ (\rho_o)^2 \qquad (6)$$

(ρ_0= bulk density at m=0)

From the data of results for relative permittivity at different decimal moisture contents and bulk densities, the constants for the first part of each of the sets of models were evaluated using the method of least-squares-fit for nonlinear regression.

The same method was adopted using the data for dielectric loss factor derived from the works of S.O.

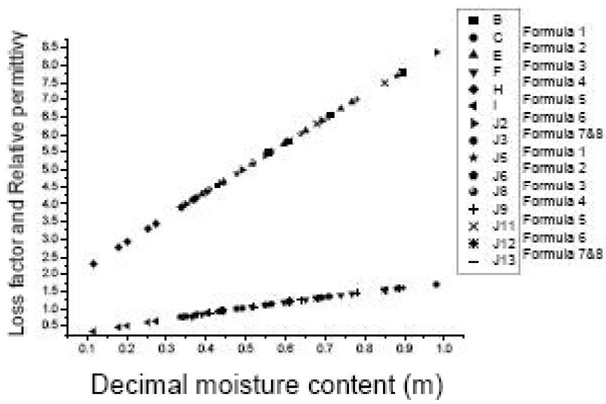

Figure 1: Variation of relative permittivy and loss factor of spring barley kernels at 2.45GHz and 24^{0}C as functions of decimal moisture content in the light of quadratic model

Nelson[7] i.e., from figure 1(b) for the operating frequency of 2450 MHz. The resulting data are presented in TABLE 1 and the evaluated constants are listed in TABLE 2.

In order to extend the applicability of the present models to grain kernels, the values of relative permittivity of the moist grain samples, (supposed to be an air-particle binary mixture), were proposed to be converted to those of solid materials (particles) with the help of eight dielectric mixture equations[7-13].

Brief introduction of the dielectric mixture equations used

1. Rother-Lichtenecker formula or the logarithmic law of mixing for Chaotic mixture[8]

$$\ln \varepsilon_r = \Sigma f_i \ln \varepsilon_i \text{(for n component mixture)} \quad (7)$$

Thus for an air-particle binary mixture

$$\ln \varepsilon_r = f_1 \ln \varepsilon_1 + f_2 \ln \varepsilon_2 \quad (8)$$

where ε_r = permittivity of the mixture, f_1 = packing fraction of air, ε_1 = permittivity of air (= 1), f_2 = packing fraction of the particles such that $f_1 + f_2 = 1$, ε_2 = permittivity of the particulate material. Also,

$$\varepsilon_2 = \exp[1/f_2 \ln \varepsilon_r] \quad (9)$$

2. Taylor's formula for random angular distribution of needles[9]

$$3\varepsilon_r(\varepsilon_r - \varepsilon_H)/f = (\varepsilon_I - \varepsilon_H)(2\varepsilon_I + \varepsilon_r) \quad (10)$$

Where ε_I = permittivity of the inclusion = ε_2, ε_H = permittivity of the host (air) = 1

Taking only the positive root of the quadratic equation which the relation (7) yielded:

TABLE 1: Data of measured values of relative permittivity and loss factor of spring barley, *Hordeum Vulgares L.* at 24^{0}C and 2450 MHz at different bulk densities and moisture contents

Moisture content %, wet basis	Bulk density in gxcm^3	Relative permittivity	Dielectric loss factor
8.2	0.588	2.05	0.284
11.3	0.597	2.28	0.328
12.8	0.600	2.36	0.375
14.9	0.595	2.54	0.409
17.4	0.592	2.68	0.437
19.7	0.602	2.92	0.484
21.1	0.601	3.05	0.512
23.4	0.586	3.26	0.575
25.1	0.588	3.17	0.597

TABLE 2: Data of evaluated constants for the different models for spring barley, *Hordeum Vulgares L.* at 24^{0}C

	Nelson's Models		Models from present study	
Models	**Quadratic**	**Cubic**	**Quadratic**	**Cubic**
(A) Models with decimal moisture content, m	A_2 = 0.317 B_2 =-0.0410 C_2 = 0.0946 D_2 = 0.0164	A_3=0.270 B_3 =-0.0101 C_3 =0.0498 D_3 =0.0082	a = -0.3256 b = 7.3844 c = –0.4760 d = 2.0891 K_1= 1.45 K_2= 0.10	a = -57.6759 b =20.8360 c =5.5789 d =45.0734 e =-17.0137 f =3.5001 K_1=1.45 K_2=0.10
(B) Models with moisture density, m_d	-	-	a = 1.3420 b = 12.1706 c = –1.7787 d = 3.5831 K_1= 1.45 K_2= 0.10	a =-187.4127 b=41.7622 c=10.1427 d=110.2285 e=-25.5522 f = 4.7758 K_1= 1.45 K_2= 0.10
(C) Models with moisture specific volume, m_v	-	-	a = –0.4274 b = 4.4882 c = –0.3289 d = 1.2996 K_1= 1.45 K_2= 0.10	a = –15.6034 b = 9.3163 c = 3.07430 d = 2.5731 e = –1.9357 f = 1.5328 K_1= 1.45 K_2= 0.10

$$\varepsilon_2 = 0.25\,[\{2+3/f\,(\varepsilon_r-1) - \varepsilon_r\} + [\,[\{2+3/f\,(\varepsilon_r-1)\} - \varepsilon_r]^2 + 8\varepsilon_r]^{1/2}] \quad (11)$$

3. Taylor's formula for random angular distribution of disks[9]

$$[3(\varepsilon_r - \varepsilon_H)(\varepsilon_I + \varepsilon_r)]/f = (\varepsilon_I - \varepsilon_H)(5\varepsilon_r + \varepsilon_I) \quad (12)$$

On similar pattern as 2, one gets

$$\varepsilon_2 = 0.5[[(1\text{-}3/f) - (5\text{-}3/f)\,\varepsilon_r] + [\{(1\text{-}3/f) - (5\text{-}3/f)\varepsilon_r\}^2 + 4\{(3/f)\varepsilon_r^2 + (5\text{-}3/f)\varepsilon_r\}]^{1/2}] \quad (13)$$

FULL PAPER

Taylor proposed a theory of elliptical inclusions of another dielectric material which could be expanded to include the case of lossy media in this case. The host medium is supposed to contain homogeneous random concentration of particles of the material with the condition that the field in the vicinity of the ellipsoid can be regarded as uniform and that $l<<\lambda$, where l is the large dimension of the ellipsoid and λ is the wave length of the wave. Also, the average field approximations are valid only for $f^2<<1$.

Lewin's formula[10]

Lewin proposed a formula for the computation of permittivity and permeability of mixture consisting of a homogenous material in which spherical particles are embedded. The formula is given as :

$$(\varepsilon_r - \varepsilon_H)/ \varepsilon_H = 3f (\varepsilon_I - \varepsilon_H)/\{\varepsilon_H(1+2f)+\varepsilon_I(1-f)\} \quad (14)$$

which in the present case simplifies as

$$\varepsilon_2 = [\varepsilon_r (1+2f) - (1-f)]/[(1+2f)-\varepsilon_r (1-f)] \quad (15)$$

Thus, the upper limit to the usefulness to the above formula should be $f\leq\pi/6$. However, it has been reported that higher values of f gave quite good agreement with the equation. Here the particles were supposed to be arranged in a cubic lattice spread in semi-infinite region, which has been reported to be valid at high frequency and hence it was supposed to be appropriate for the microwave frequency region of the measurement of permittivities.

Sillars formula[11]

$$\varepsilon_r = \varepsilon_H [\varepsilon_H + D(1-f)+f][\varepsilon_I - \varepsilon_H] / [\varepsilon_H + D(1-f)(\varepsilon_I - \varepsilon_H)] \quad (16)$$

Where D = depolarization factor depending on the shape of the particles.

For the present case the formula reduces to

$$\varepsilon_r = [1+\{D(1-f)+f\}(\varepsilon_r -1)]/[1+D(1-f)(\varepsilon_2 -1)]$$

$$\Rightarrow \varepsilon_2 = [\{\varepsilon_r - 1\}/\{f-D(1-f)(\varepsilon_r - 1)\}]+1 \text{ (where D= 0.2)} \quad (17)$$

Surprisingly enough, the data give the best fit for the value of D = 0.2, as derived for rutile particles, suggesting that the shape of the particles were the same in both the cases. Other wise, other values of D were to be tried for best fit.

Sadiku's formula[12]

$$(\varepsilon_r - 1)/ (\varepsilon_r + u) = f (\varepsilon_I -1)/(\varepsilon_2 +u) + (1-f) (\varepsilon_H -1)/ (\varepsilon_H + u) \quad (18)$$

For the present case, $\varepsilon_H = 1$ and $\varepsilon_I = \varepsilon_2$ as before and thus giving rise to

$$(\varepsilon_r - 1)/ (\varepsilon_r + u) = f (\varepsilon_2 -1) /(\varepsilon_2 + u) \quad (19)$$

In the above formula u = form no., supposed to be depending on the shape of the particles and the values of u= 5 for snow or ice taken from the literature, gave the best fit as D = 0.2 for rutile in the previous formula. It also led us to suppose that there must be a relation like D = 1/u between D and u. Thus, by putting u= 5, the formula finally reduces to:

$$\varepsilon_2 +2 = 3 [\varepsilon_r (1+f) + (5f-1)]/[(1+5f)- \varepsilon_r(1-f)] \quad (20)$$

Again, the limitation for the validity of the Weiner formula is that the particles should be small as compared to the wavelength used.

Formula obtained from effective medium theory[13]

$$\varepsilon_r = \varepsilon_H [(1+2f) \varepsilon_I +2 \varepsilon_H (1-f)]/[\varepsilon_I(1-f) + (2+f)\varepsilon_H] \quad (21)$$

Like other cases, $\varepsilon_H = 1$ and $\varepsilon_I = \varepsilon_2$ gives rise to :

$$\varepsilon_2 = [(2+f) \varepsilon_r -2(1-f)]/[(1+2f-\varepsilon_r(1-f)] \quad (22)$$

In the above formula, particulate material has been taken as the first component and air as the second one under the limiting case of small concentration of the component A in the binary system AB-opposed to those taken in other formulae.

Skipetrov formula[14]

$$\varepsilon_{eff} = \varepsilon_1 [1\{3f_2 (\varepsilon_2 - \varepsilon_1)\}/\{\varepsilon_1(2+f_2)+\varepsilon_2(1-f_2)\}] \quad (23)$$

For the present case

$$\varepsilon_{eff} = \varepsilon_r ; \varepsilon_1 = \varepsilon_H = 1 ; f_2 = f \text{ (say)}$$

The equation finally gives :

$$\varepsilon_r = 1 + [3f (\varepsilon_2 - 1)]/[(2+f)+\varepsilon_2(1-f)] \quad (24)$$

The above expression has been supposed to be an original expression for the effective dielectric function of dilute suspension of spherical beads of diameter $d<<\lambda$. Further, it has been claimed that the above formula is expected to be more appropriate for the interpretation of the experiments and behavior at higher volume fractions.

In all the above equations, except the last one, air has been taken as the first component and the particulate material as the second one.

Using any measured value of ε_r, the corresponding value of volume fraction of the particle, f_2= (f), the value of the permittivity of the particles, ε_2 (=ε_2, say) was

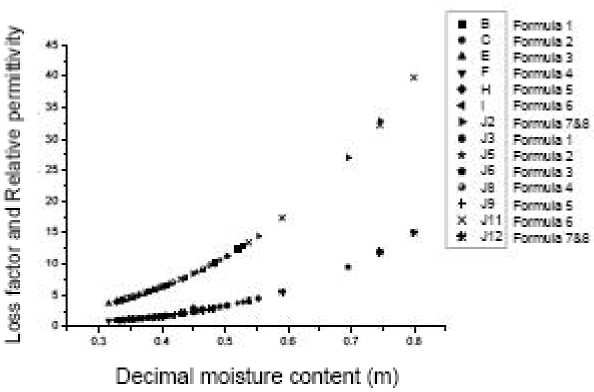

Figure 2: Variation of relative permittivity and loss factor of spring barley kernels at 2.45GHz and 24^{0}C as functions of decimal moisture content in the light of cubic model

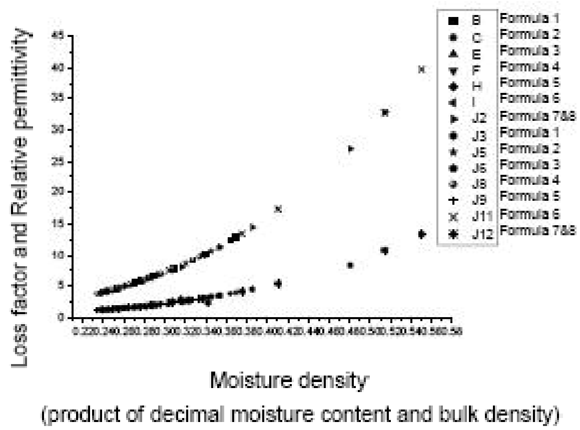

Figure 4: Variation of relative pemittivity and loss factor of spring barley kernels with kernels 2.45GHz and 24^{0}C as function of moisture density in the light of cubic model at

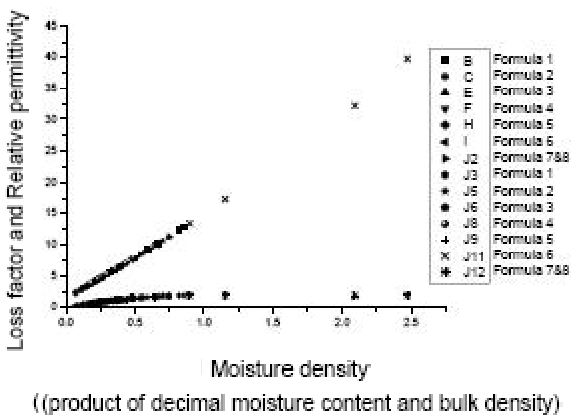

Figure 3: Variation of relative pemittivity and loss factor of spring barley kernels with kernels at 2.45GHz and 24^{0}C as function of moisture density in the light of quadratic model

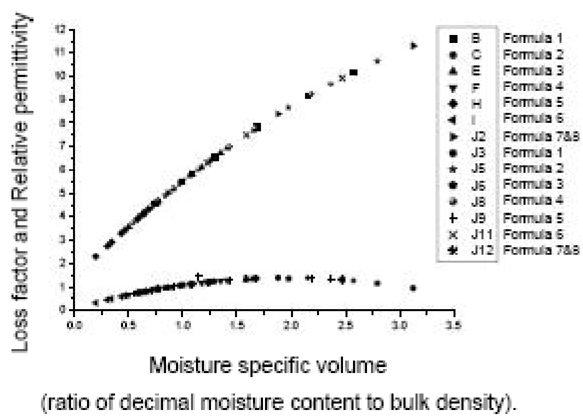

Figure 5 : Variation of relative permittivity and loss factor of spring barley kernels at 2.45GHz and 24^{0}C as functions of moisture specific volume in the light of quadratic model

calculated choosing any of the eight equations, say the first one. The constants of the first set of equations concerning relative permittivity versus m (say) for the quadratic or the cubic model, as the case may be, were used to compute the value of m, (say). Using these values of m and the constants evaluated for the second set of equations (concerning loss factor versus moisture content, say), the value of loss factor of the particles (kernels), ε_2'' were calculated. Thus one gets the values of ε_2' and ε_2'' for a given computed value of m (say). The same process was repeated for different values of volume fractions of a given sample. A similar process was adopted by taking another dielectric mixture equation one by one, to get the data points. The some process was repeated for computation of ε_2' and ε_2'' as functions of m_d and m_v for both types of the proposed models. It was expected to achieve the estimates of ε_2' and ε_2'' of spring barley kernels as functions m, m_d and m_v.

RESULTS AND DISCUSSION

Data of measured values of relative permittivity and loss factor at 2.45 GHz and 24^{0}C and at nine moisture contents are illustrated in TABLE 1. Instead of reporting the whole set of data for computed values of ε_2' and ε_2'' resulting from the different dielectric mixture equations and computed values of m, m_d and m_v, only the evaluated constants of the different models have been presented in TABLE 2. The results are shown graphically in figure 1 through 6. The models and plots showed their usefulness for practical applications. Further, the quantitative relative performances of the present models as compared with those of Nelson are reported in TABLE 3. The coefficients of determination (r^2) and average percentage errors of prediction for each of the different models have also been reported.

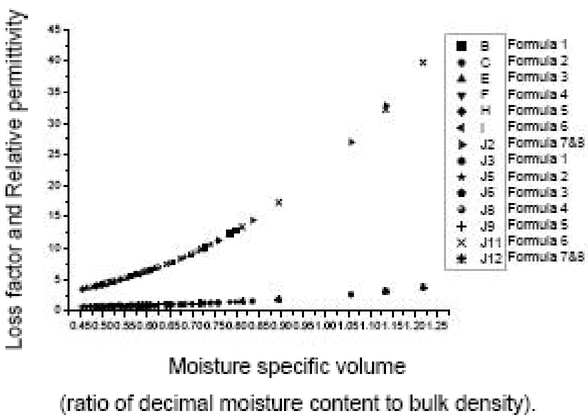

Figure 6 : Variation of relative permittivity and loss factor of spring barley kernels at 2.45GHz and 24^{0}C as functions of moisture specific volume in the light of cubic model

Examination of data in TABLE 3 reveals that the quadratic and cubic models of Nelson relating relative permittivity and decimal moisture content generally predicted almost the same values and in only a few instances did they disagree with measured values by greater than 5 %. The average error of prediction over all moisture contents was 3.6 for the quadratic model and 3.5 for the cubic model. The corresponding average errors of prediction for the present two models are 1.4 % and 1.5 %. The main difference that is observed is that Nelson's cubic model gives little better performance as compared to quadratic model whereas reverse is the case with the present models. The average error of prediction with the Nelson's only one model for the loss factor against decimal moisture content is a bit higher ≈24.8 % while with the corresponding two models proposed in the present study the errors are ≈0.4 % and 0.6 % respectively.

TABLE 3: Comparative performances of different models for the variation of relative permittivity and loss factor with moisture content of spring barley samples at 24^{0}C and 2.45 GHz

(A)

Nelson's model (NM) for relative permittivity				Present models for relative permittivity			
QM+		CM++		QM		CM	
Predicted values	r^2/Average % error	Predicted values	r^2/Average % error	Predicted values	r^2/Average % error	Predicted values	r^2/Average % error
2.121		2.122		2.053		2.016	
2.357		2.353		2.280		2.263	
2.475		2.469		2.390		2.384	
2.615		2.606		2.543		2.553	
2.795	0.997/3.615	2.784	0.998/3.468	2.725	0.999/1.408	2.748	0.997/1.501
3.018		3.012		2.892		2.917	
3.129		3.124		2.994		3.013	
3.248		3.242		3.160		3.157	
3.400		3.400		3.283		3.251	

(B)

Nelson's model (NM) for loss factor		Present models for loss factor			
		QM		CM	
Predicted values	r^2/Average % error	Predicted values	r^2/Average % error	Predicted values	r^2/Average % error
0.115		0.268		0.298	
0.178		0.330		0.343	
0.216		0.359		0.364	
0.270		0.401		0.393	
0.346	0.986/24.818	0.449	0.999/0.406	0.431	0.977/0.556
0.444		0.493		0.474	
0.499		0.579		0.504	
0.572		0.563		0.565	
0.655		0.594		0.619	

+QM – quadratic model ; ++CM– cubic model

Also presented in TABLE 1 are the coefficients of determination with the different models which show that all of them provide good fittings with experimental data in having $r^2 \approx 0.99$. However, a little better fitting with the new quadratic model is indicated (having $r^2 \approx 0.999$).

CONCLUSION

The results derived from the models are indicative of the fact that these equations should be generally useful for predictive purposes in most practical applications i.e., they provide a means for estimating the dielectric properties of the individual kernels of spring barley, Hordeum Vulgares L. at a temperature of 24^0C measured at 2.45GHz and over the moisture content range from about 8 % to 25 %, wet basis.

REFERENCES

[1] S.O.Nelson; J.Microwave Power, **12(1)**, 67 **(1977)**.
[2] S.O.Nelson; IEEE Trans Electrical Insulation, **26(5)**, 845 **(1991)**.
[3] S.O.Nelson; Trans ASAE, **28(1)**, 234 **(1985)**.
[4] S.O.Nelson; Trans ASAE, **28(6)**, 2047 **(1985)**.
[5] S.O.Nelson; Trans ASAE, **29(2)**, 607 **(1986)**.
[6] S.O.Nelson; Trans ASAE, **30(5)**, 1538 **(1987)**.
[7] S.H.Noh and S.O.Nelson; Trans ASAE, **32(8)**, 991 **(1989)**.
[8] P.Debye; 'Polar Molecules', The Chemical Catalog Co; NewYork, **(1929)**.
[9] L.S.Taylor; IEEE Trans.Antennas & Propag, USA, **13**, 943 **(1965)**.
[10] E.Lewin; J.IEEE, **94(3)**, 65 **(1947)**.
[11] R.W.Sillars; J.Appl.Phys., USA, **47(4)**, 1708 **(1976)**.
[12] M.N.O.Sadiku; Appl.Opt, **24**, 572 **(1985)**.
[13] Itzhak Webmann; Joshua Jortner, Morrel H.Cohen; Physical Review, **15(12)**, 5712 **(1977)**.
[14] S.E.Skipetrov; Physical Review, **60(18)**, 12705 **(1999)**.