New Density-Independent Model for Measurement of Grain Moisture Content using Microwave Techniques

Jong-Heon Kim, Ki-Bok Kim, and Sang-Ha Noh

Abstract

A free space transmission method using standard gain horn antennas in the frequency range from 9.0 to 10.5GHz is applied to determine the dielectric properties of grain such as rough rice, brown rice and barley. The dielectric constant and loss factor, which depend on the moisture content of the wetted grain are obtained from the measured attenuation and phase shift by vector network analyzer. The moisture content of grain varied from 11 to 25% based on its wetted condition. The measured values of dielectric constants as a function of moisture density are compared with values of those obtained using the predicted model for estimating dielectric constants of grain. The effect of density fluctuation, which is an important parameter governing the dielectric properties of grain, on the dielectric constant and loss factor is presented. A new density-independent model in terms of measured attenuation and moisture density is proposed for reducing the effects of density fluctuation on the moisture content measurement.

I. Introduction

The moisture content of agricultural products very much influences their physical and chemical properties and hence, is an important parameter governing their storage, processability and quality. Several methods are proposed to measure the moisture contents, but the resistivity cell method and parallel plate capacitor method are commonly used.

The moisture content measurement using the resistivity cell method uses the principle of decreasing of resistance due to increased moisture content of grain[1]. For measurement using this method the grain samples must be crushed to stabilize the contact resistance between samples and electrodes. In this case the measured values vary with respect to the variation of the pressure and repeated measurements are necessary. The errors in the measured values at high moisture content are greater than other method because there is very small variation of resistance at high moisture contents (over 20%). The advantages of this method are simple implementation and low cost.

The parallel plate method measures the capacitance of the sample between two electrodes forming a capacitor and from which the dielectric constant of the grain is calculated[2]. This method can be used with a wide range of moisture contents and it is not necessary to destruct the samples. This method can be used at high frequencies up to 30MHz.

In the microwave frequency range transmission line method using a waveguide or a coaxial airline and resonant cavity method are mainly employed[3, 4]. The disadvantages of this method are the requirement of the precise fabrication of the sample holders and the limitations of the non-contactive measurement.

As on-line machinery are being recently used in storage and processing of grain, the development of non-destructive and non-contactive measurement technology for measuring the moisture content of grain is required. Free space microwave measurement method is a very useful for on-line measurement of the moisture content[5-7].

In this paper the free space microwave measurement method using standard horn antennas is presented for determining the complex permittivity of grain which depends on the moisture content (from 11% to 25% on its wetted condition). A grain samples of rough rice, brown rice and barley with varying moisture content, bulk density and moisture density are used. The attenuation and phase shift of the microwave signal through the wetted grain samples are measured by vector network analyzer in X-band frequency range. The complex permittivities of the wetted grain are calculated from the measured attenuation and phase shift for various values of moisture content and bulk density. The measured values of dielectric constants as a function of moisture density are compared with values of those obtained using the predicted model for estimating dielectric constants of grain.

One of the ciritical parameters in moisture content measurements

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is the variation of bulk density. Since attenuation and phase shift increase with higher bulk density, the density influence must be eliminated for accurate measuring of moisture content. Some methods for reducing the effects of density variation are presented. In this paper a new density-independent model for microwave measurement of grain moisture is proposed and the results obtained using this model are compared with those obtained using existing models by means of the statistical analysis.

II. Microwave Dielectric Property

The microwave moisture content measurement uses the absorption of microwave energy corresponding to the rotational energy of water molecule. When the electrical field is applied to a dielectric material, electromagnetic energy is dissipated in the dielectric materials due to dipole polarization. The interaction of the applied electromagnetic field with wetted grain can be described by the complex permittivity;

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (1)$$

The real part of the complex permittivity ε' is called the dielectric constant and the imaginary part ε'' is called the dielectric loss factor. The dielectric constant describes the ability of a material to store electric energy while the dielectric loss factor represents the loss of electric field energy in the material. When a plane wave is incident normally upon a dielectric medium as shown in Fig. 1, part of it is transmitted into the medium and part is reflected at the interface between free space and the dielectric medium.

The complex propagation constant of a plane wave in a lossy dielectric medium is given by

$$\gamma = \alpha + j\beta \quad (2)$$

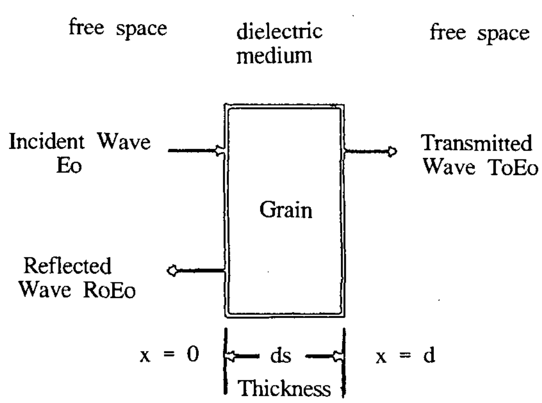


Fig. 1. A wave incident on a plane boundary between free space and dielectric medium.

where α is the attenuation constant in Np/m and β is the phase constant.

The propagation constant may be expressed in terms of the complex permittivity of dielectric material;

$$\alpha + j\beta = j\sqrt{\left(\frac{\omega}{c_0}\right)^2 (\varepsilon' - j\varepsilon'')} = j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon' - j\varepsilon''} \quad (3)$$

where c_0 is the speed of light and λ_0 is the wavelength in free space.

With

$$\beta_0 = \frac{2\pi}{\lambda_0} \quad (4)$$

and

$$(\alpha + j\beta)^2 = -\beta_0^2(\varepsilon' - j\varepsilon'') \quad (5)$$

the dielectric constant and loss factor can be expressed in terms of the attenuation constant and phase constant per unit length in the medium as

$$\varepsilon' = \frac{1}{\beta_0^2}(\beta^2 - \alpha^2) \quad (6)$$

$$\varepsilon'' = \frac{1}{\beta_0^2} 2\alpha\beta \quad (7)$$

The difference between the phase shifts with and without grain samples is given by

$$\triangle\Phi = \Phi_s - \Phi_a = (\beta_s - \beta_a)d \quad (8)$$

where Φ_s is the phase shift with sample, Φ_a is the phase shift without sample, β_s is the phase constant with sample, β_a is the phase constant without sample and d is thickness of the sample. From the relationship between phase constant and the dielectric constant

$$\beta_s^2 = \left(\frac{\triangle\Phi}{d} + \beta_a\right)^2 = \beta_0^2\varepsilon' + \alpha^2 \quad (9)$$

the dielectric constant can be expressed in terms of the measured values as follows;

$$\varepsilon' = 1 + \left(\frac{\triangle\Phi}{\beta_0 d}\right)^2 + 2\left(\frac{\triangle\Phi}{d}\right)\frac{\beta_a}{\beta_0^2} + \left(\frac{\alpha}{\beta_0}\right)^2 \quad (10)$$

where

$$\beta_s = \beta_0 \quad (11)$$

and

$$\left(\frac{\alpha}{\beta_0}\right)^2 \ll 1 \quad (12)$$

Finally, the dielectric constant is given as a function of the measured phase shift:

$$\varepsilon' = \left(1 + \frac{\triangle \Phi \lambda_0}{360d}\right)^2 \quad (13)$$

From the difference between the attenuation with and without grain samples given by

$$\triangle A = A_s - A_a = (\alpha_s - \alpha_a)d \quad (14)$$

where A_s is attenuation with sample in dB, A_a is attenuation without sample in dB, α_s is the attenuation constant with sample in dB/m, α_a is the attenuation constant without sample in dB/m, with

$$\alpha_s = \frac{\triangle A}{d} + \alpha_a \quad (15)$$

the loss factor is obtained by

$$\varepsilon'' = \frac{\triangle A \lambda_0 \sqrt{\varepsilon'}}{8.686\pi d} \quad (16)$$

Ⅲ. Free Space Measurement Set Up

A block diagram of the experimental set up used to measure the attenuation and phase shift of microwave signal through the grain samples is shown in Fig. 2.

In this setup, a pair of a X-band standard gain horn antennas with 7.9cm×5.4cm and 16.5dB gain are mounted on an acrylic plate stand. The horns are connected to the two ports of the HP8510C network analyzer via waveguide/coaxial adaptors. Between the transmit and receive horns the sample holder is mounted. The sample holder is a rectangular container made of acrylic plates with 2mm wall thickness. The width of the sample holder must be large enough to cover the signal between the antennas and the thickness of that be greater than one wavelength for using the wave propagation method. The dimensions of the sample holder used in this experiment are 42.5mm thickness, 119.6mm width and 155.2mm height.

The network analyzer was calibrated in the CW transmission mode with the through connection of transmit and receive antennas to measure the S_{21}-parameter for transmission coefficient. The attenuation and phase shift due to the wetted grain samples are obtain from the measured S_{21} value. The attenuation is derived from the magnitude of S_{21} and the phase shift from the phase of S_{21} as follows;

$$S_{21} = |S_{21}| \exp(j\Phi) \quad (17)$$

$$A = -20 \log |S_{21}| \quad (18)$$

$$\Phi = 2\pi n + \varphi \quad (19)$$

where A is the attenuation, Φ is total phase, ϕ is phase shift and n is integer number.

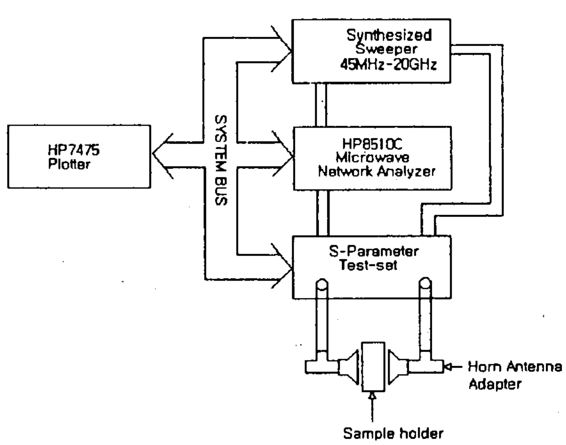


Fig. 2. Block diagram of microwave free space measurement set up.

Ⅳ. Density-Independent Model

Since the determination of dielectric properties is influenced by the amount of sample mass which interacts with the electromagnetic field, the bulk density defined by

$$\rho_m = \frac{m_w + m_d}{V} \quad (20)$$

where m_w is the mass of water, m_d is the mass of dry grain and V is the volume of the sample holder, is an important factor affecting the dielectric properties of grain.

For the microwave moisture content measurement the measured attenuation is directly affected by the variation of the bulk density and thus the fluctuation in density is the main source of error. There are some methods to compensate the effect of bulk density fluctuations. The density-independent method proposed by Meyer is based on the simultaneous measurement of the dielectric constant and loss factor[8]. The density-independent calibration factor is given by

$$\frac{\varepsilon' - 1}{\varepsilon''} \quad (21)$$

However, the use of this factor is valid only for the small range of densities. For a wide range of densities this factor cannot compensate the effect of the density fluctuation well. An improved method for reducing the effects of density over a broader range of density is reported by[9]

$$\frac{\Phi}{A} = \frac{\varepsilon' - 1}{\varepsilon''} \cdot \frac{2\sqrt{\varepsilon'}}{\sqrt{\varepsilon'} + 1} \quad (22)$$

In this paper a new density-independent model using the moisture density is introduced. The moisture density is defined as product of bulk density by the moisture content;

$$\rho_m = \rho_b \Psi \quad (23)$$

with

$$\Psi = \frac{m_w}{m_w + m_d} \times 100\% \quad (24)$$

where ψ is moisture content based on its wetted condition.

V. Experimental Results

For this work, short grain rough rice, brown rice and barley were harvested in 1996 at a farm attached to the college of agriculture and life science at Seoul National University. The grain samples with several moisture contents are prepared for the measurement by a standard forced-air oven method (Table 1). In this standard oven method, the moisture content is determined by drying grain samples with 10g weight for 24hours at 135℃[10].

Table 1. Moisture contents of rough and brown rice and barley samples.

Item	Varieties	Range of Moisture Content
Rough Rice	Hwasung	11~25%
Brown Rice	Ilpoom	11~18%
Barley	Jinyang	11~21%

The dielectric properties of grain with various moisture contents are determined by measuring the attenuation and phase shift of the microwave signal through the grain samples in the frequency range from 9.0 to 10.5GHz. The grain samples are naturally filled in the sample holder and the bulk density of samples varied from 0.546 to 0.606g/cm^3 for rough rice, from 0.777 to 0.808 g/cm^3 for brown rice and from 0.627 to 0.697g/cm^3 for barley at the temperature 24℃ respectively.

The variation in the dielectric constant and loss factor of these grain samples with various moisture contents is illustrated in Fig. 3 in the frequency range from 9.0 to 10.5GHz. The dielectric constant and loss factor are found to increase with the moisture content.

The measured values of dielectric constants as a function of moisture density are compared with values of those obtained using the predicted quadratic model for estimating dielectric constants of rough rice as given below[11];

$$\varepsilon' = [1 + (a - b\log f + c\Psi - d\Psi \log f)\rho_m] \quad (25)$$

where a, b, c and d are constants, f is frequency and ρm is moisture density.

The comparisons of measured and predicted values of dielectric constant in frequency range of 9.0GHz and 10.5 GHz show that the measured values are in good agreement with the predicted quadratic model(Fig. 4).

Dependence of the dielectric constant and loss factor of grain samples on its bulk density is determined for rough rice, brown rice and barley at 9.5GHz, and results are shown in Fig. 5.

It is clear that the fluctuations in bulk density result in different values of the dielectric constant and loss factor depending on the types of grain samples. The dielectric constant and loss factors are found to increase with the bulk density.

A new density-independent model proposed for reducing the effects of density variation on the moisture measurement is compared with an existing model by the regression analysis using the statistical analysis software (SAS). The regression model expressing relationship between the ratio of phase shift to attenuation and moisture content is given by

$$\frac{\Phi}{A} = a \times \Psi + b \quad (26)$$

A new density-independent function is developed in terms of measured attenuation and moisture density;

$$A = a \times \rho_m + b \quad (27)$$

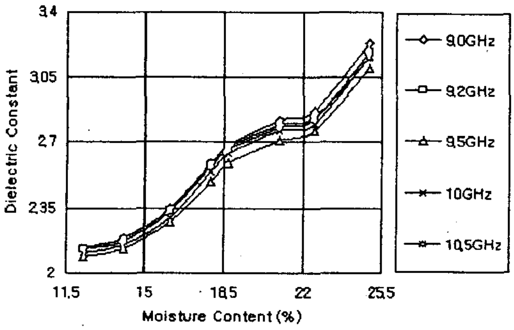
where a and b are coefficients.

The result of the regression analysis of this model for rough rice is shown in Table 2 for the frequency range of 9.0GHz to 10.5GHz, and the ratio of phase shift to attenuation and moisture content as a function of moisture content at 9.5GHz is plotted in Fig. 6. The coefficients of determinants obtained for rough rice are from 0.91 to 0.93.

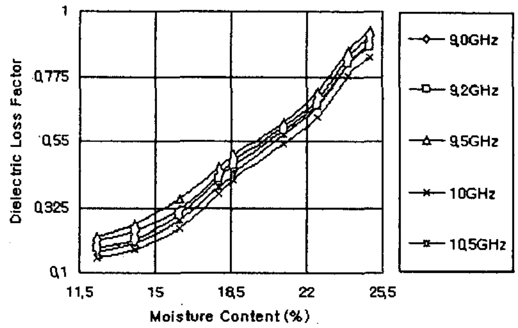
The regression analysis of new model for rough rice are given in Table 3. The attenuation for them as a function of moisture density at 9.5GHz is shown in Fig. 7. The coefficients of determinants for rough rice determined using new model are from 0.98 to 0.99. Because of the high coefficients of determinants, the new density-independent model is very suitable for the prediction of moisture content of grain, independent on the density variation.

VI. Conclusions

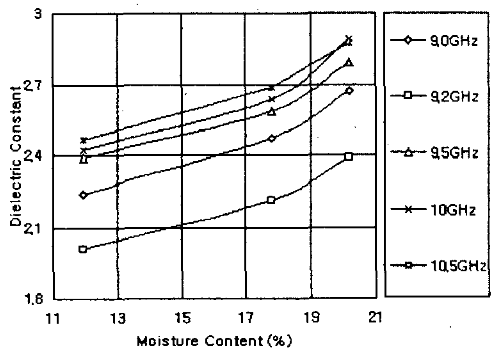
Dielectric constants and loss factors of rough rice with moisture content in the range of 11 to 25%, brown rice in the range of 11 to 18% and barley in the range of 11 to 21% based on wetted condition are determined from the measured attenuation and phase shift of the transmitted microwave signal through the grain samples using vector network analyzer. The free space transmission method using standard gain horn antennas is used for non-destructive and non-contactive measurement in the frequency



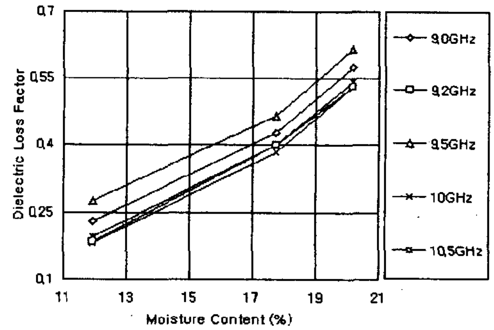
(a-1) Dielectric constant for rough rice



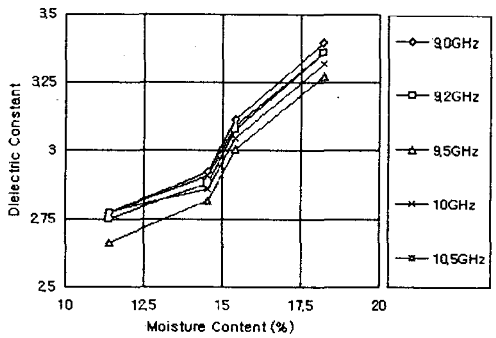
(a-2) Dielectric loss factor for rough rice



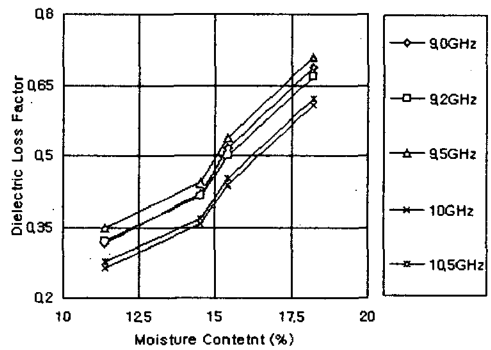
(b-1) Dielectric constant for brown rice



(b-2) Dielectric loss factor for brown rice

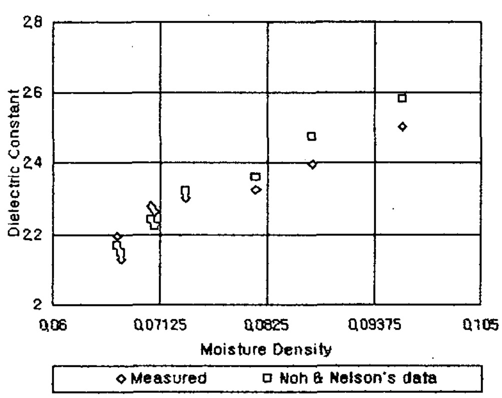


(c-1) Dielectric constant for barley

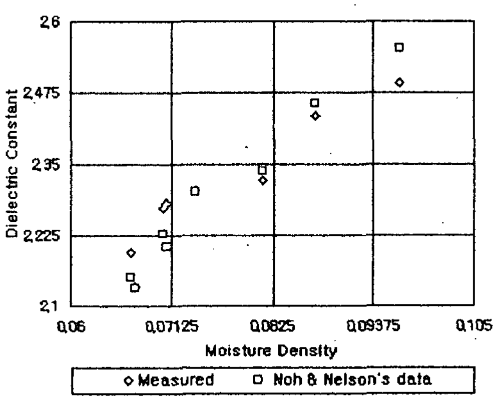


(c-2) Dielectric loss factor for barley

Fig. 3. Moisture content dependence of the dielectric properties of (a) rough and (b) brown rice and (c) barley samples.

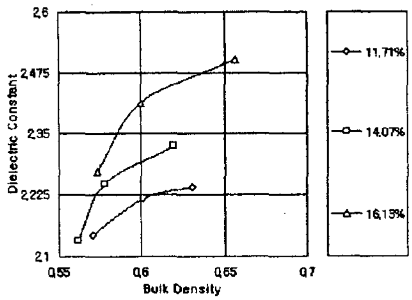


(a) at 9.0GHz

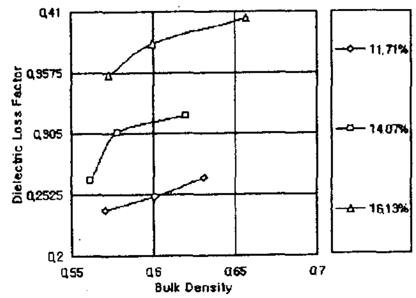


(b) at 10,5GHz

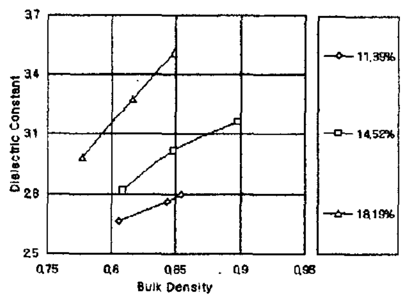
Fig. 4. Comparison of measured and predicted values of dielectric constant as a function of moisture density with prediction model.



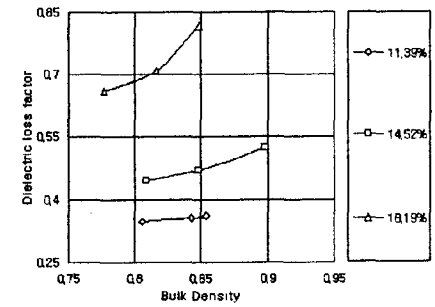
(a-1) Dielectric constant for rough rice



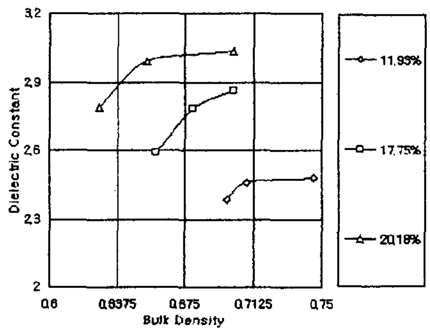
(a-2) Dielectric loss factor for rough rice



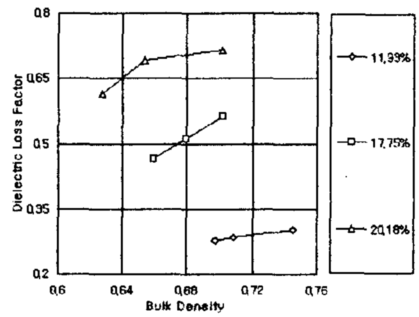
(b-1) Dielectric constant for brown rice



(b-2) Dielectric loss factor for brown rice



(c-1) Dielectric constant for barley



(c-2) Dielectric loss factor for barley

Fig. 5. Bulk density dependence of the dielectric properties of (a) rough, (b) brown rice and (c) barley samples at 9.5gHz.

Table 2. Regression analysis expressing relationship between the ratio of phase shift to attenuation and moisture content of rough rice.

f(GHz)	a	b	R^2	SEC
9	-1.5793	60.1468	0.9369	1.9864
9.2	-1.9999	69.5475	0.9134	2.9865
9.5	-1.2901	51.9702	0.9363	1.6321
10.0	-2.5267	85.9999	0.9181	3.9030
10.5	-2.1850	78.0023	0.9325	3.0400

Table 3. Regression analysis expressing relationship between the moisture density and attenuation of rough rice.

f(GHz)	a	b	R^2	SEC
9	156.090	-6.3462	0.9849	0.5330
9.2	162.962	-7.2175	0.9925	0.4369
9.5	160.544	-5.8134	0.9919	0.4462
10.0	179.175	-9.0985	0.9894	0.5735
10.5	194.261	-9.5194	0.9878	0.6654

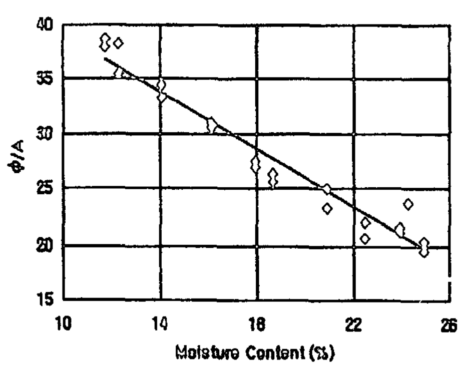


Fig. 6. Relationship between the ratio of phase shift and attenuation and moisture content of rough rice at 9.5GHz.

range from 9.0 to 10.5GHz.

The measured dielectric constant and loss factor are in good agreement with those obtained using the prediction model for estimating dielectric constants of rough rice. A new density-

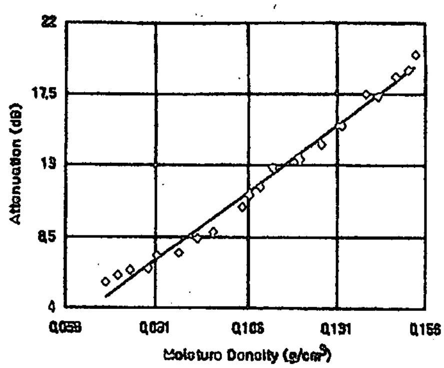


Fig. 7. Relationship between the moisture density and attenuation of rough rice at 9.5GHz.

independent model in terms of measured attenuation and moisture density is proposed and the results obtained using this model are compared with those obtained by existing model using the ratio of phase shift to attenuation. From the results of the comparison between these models using the regression analysis, the new model results in higher values of determinant coefficients than those with the other models. Therefore this new model can be uses for the compensation of the effect of the density dependence on the moisture content measurement.

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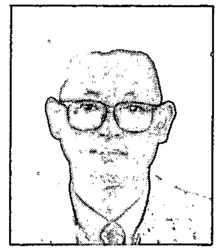

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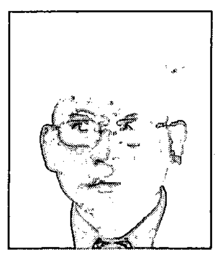

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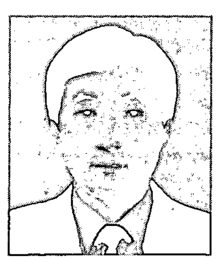

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