



e-ISSN: 2319-8753 | p-ISSN: 2320-6710

IJRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 10, Issue 3, March 2021

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 7.512

9940 572 462

6381 907 438

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Mathematical Model of Interaction Ultra High Frequency Wave with Wet Grain

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ABSTRACT: Grain and grain products for the Republic of Uzbekistan have an important economic indicator. The quality indicators of grain strongly depend on their moisture content, which constantly changes during storage and processing, therefore it should be controlled. In a theoretical study, a wet material is presented as consisting of three flat layers: water, dry matter and air. The moisture conversion function is obtained, based on a layered model of the interaction of a microwave electromagnetic wave with a wet grain. The advantages of the amplitude-phase method for more accurate measurements in laboratory conditions are shown.

KEYWORDS: grain moisture, microwave method, transformation function, dielectric parameters, microwave generator, attenuation coefficient, dielectric constant, magnetic permeability, phase shift of an electromagnetic wave.

I. INTRODUCTION

In recent years, significant results have been achieved in the field of providing grain to the Republic of Uzbekistan: the sowing volume has increased, the harvest has been brought to more than 5 million tons in 2020 against 900 thousand tons in 1991.

The moisture content of grain during storage and processing is constantly changing, so it should be monitored to take timely and appropriate measures to prevent adverse events [1].

It is known that one of the promising methods for measuring moisture content is the ultrahigh frequency (microwave) method [2]. Moisture control by the method of ultra-high frequency provides for the effect on the controlled material of an alternating electromagnetic wave, in which information on moisture is presented as a function of two variables (attenuation and phase shift of the electromagnetic wave).

II. RELATED WORK

Let us consider the theoretical aspects of the derivation of the function of converting grain moisture in the microwave range. In accordance with the theory of dielectrics, the investigated materials, which are in an electromagnetic field, do not show frequency and temperature anomalies in a dehydrated state. Therefore, all dependencies that are observed in grain are inherent in water in a wet state, because water makes up the bulk of the wet material. In this case, the electromagnetic field, interacting with the water molecules contained in the material, changes its electrical characteristics.

This change, which characterizes humidity, underlies all developed methods and devices for measuring humidity at microwave frequencies.

III. METHODOLOGY

A plane electromagnetic wave, emitted by a directional transmitting antenna, is incident on a controlled non-conductive material of thickness d , in the form of a rectangular parallelepiped.

When the electromagnetic energy reaches the "air - controlled material" boundary, it will partially reflect from the interface (P_{ref}), partially pass into the material, propagating in it in the direction from the transmitting antenna to the

receiving antenna. When the wave propagates inside the material, energy is absorbed (P_{abs}). Absorption is a function of dielectric parameters (ϵ - dielectric and μ - magnetic permeability) and material thickness.

IV. EXPERIMENTAL RESULTS

The energy passed through the material to the "controlled material - air" interface is partially reflected towards the transmitting antenna and is perceived by the receiving antenna. The magnitude of the recorded signal is determined by the power of the microwave generator, the dielectric parameters of the material, and the reflection from the interfaces "air - controlled material" and "controlled material - air".

If there is no reflection from the "air - controlled material" and "controlled material - air" interfaces [3-10], then the value of the electric field strength at any point on the Z axis (which corresponds to the direction of wave propagation) of the controlled material can be described by the equation:

$$E_z = E_0 e^{-\alpha Z}, \quad (1)$$

where Z is the coordinate in the direction of wave propagation;

E_0 - is the field strength for $Z=0$;

E_z - field strength at a given point;

α - microwave attenuation coefficient.

For wet materials, the damping factor is determined by the following formula:

$$\alpha = \omega \sqrt{\frac{\mu \epsilon'}{2} \sqrt{1 + \text{tg}^2 \delta} - 1},$$

where ω - is the circular frequency of the wave;

ϵ' - the real part of the dielectric constant;

$\text{tg} \delta$ - loss tangent representing the ratio of conduction currents to displacement currents;

μ - magnetic permeability, for non-conductive materials $\mu \approx 1$, $\text{tg} \delta \ll 1$, then

$$\alpha \approx \omega \sqrt{\frac{\mu \epsilon' \text{tg}^2 \delta}{2}} = \pi f \text{tg} \delta \sqrt{\epsilon'} \quad (2)$$

where f - is the linear frequency of the microwave wave.

Putting (2) in (1), we get: $E_z = E_0 e^{-\pi f \text{tg} \delta \sqrt{\epsilon'} Z}$ (3)

It is known that the power of the electromagnetic wave is $P \sim E^2$. Then

$$P_z = P_0 e^{-\omega \text{tg} \delta \sqrt{\epsilon'} Z},$$

where P_0 - is the power of the microwave generator;

P_z - is the power recorded by the receiver at this point.

If for materials $Z=d$, then the attenuation of the electromagnetic wave N (dB) in the area of the receiving antenna will be equal to:

$$N = 10 \lg \frac{P_0}{P_z} = 10 \lg e^{2\alpha d} = 20 \alpha d \lg e = 8,686 \alpha d \quad (4)$$

When studying the physical properties of materials, one most often has to deal with heterogeneous media - wet grain, consisting of a dry phase (endosperm and shell), water and air, as well as various impurities.

In a theoretical study, a wet material is represented as consisting of three flat layers: water, dry matter and air.

Let's denote the volume of water through V_w , the dry phase of the material - through V_d . Then the volume of air in the pores of the material will be $V_p = I - V_w - V_d$. Taking into account that the density of water is equal to one, we obtain $V_w = Q$, where Q is the volumetric moisture. Then the equation for determining the damping coefficient α can be written



in the following form:

$$\alpha = \alpha_w Qk + \alpha_d V_d + \alpha_a (1 - V_w - V_d), \tag{5}$$

where $\alpha_p, \alpha_d, \alpha_w$ - attenuation coefficients, respectively, of water, dry matter and air;
 Q - volumetric humidity, V_w and V_d - volume of dry matter and air; k - is an empirical constant that takes into account the structure of the material.

Simplifying expression (5) and taking into account that $\alpha_p \ll \alpha_{dry} \ll \alpha_w$, we obtain the transformation function:

$$a = \alpha_w Qk = \alpha_w W_1 \rho' k, \tag{6}$$

where Q - is the volumetric moisture content of the material;
 W_1 - relative humidity;

$\rho' = \frac{\rho_{wm}}{\rho_w}$ - reduced density, numerically equal to the density of the wet material;
 ρ_{wm} - density of wet material;
 ρ_w is the density of water.

Substituting expression (6) into formula (4), we get:

$$N = 8,686 \alpha_w W_1 \rho' k d. \tag{7}$$

Bearing in mind that the water attenuation coefficient is equal $\alpha_w = \omega t g \delta_w \sqrt{\epsilon_w}$, then from formula (7) we have

$$N = 8,686 k \omega t g \delta_w \sqrt{\epsilon_w} d W_1 \rho'. \tag{8}$$

From here

$$W_1 = N / (8,686 k \omega t g \delta_w \sqrt{\epsilon_w} \rho' d). \tag{9}$$

Taking into account the selected type of primary measuring transducer, the relationship between the total attenuation N_Σ and the bulk moisture content of the grain Q is expressed by the equation [4]

$$N_\Sigma = N_0(d) + N_{ref}(d, \epsilon^*, S, t) + 8,686 \alpha_w d Q \tag{10}$$

where $N_0(d)$ - is the initial attenuation (in the absence of material);
 N_{ref} - reflection power losses;
 $Q = \rho W$ - volumetric moisture.

As mentioned above, the dielectric properties of water in a grain depend on temperature. Moreover, the temperature coefficient in general changes not only its value, but also its sign. However, in a certain range, for the case of measuring grain moisture, the characteristic range is $10\% < W < 17\%$, it can be considered approximately constant. Then the conversion function for amplitude converters will be:

$$N_\Sigma = N_0 + 8,686 \left\{ \alpha + k(t - t_0) \right\} d Q - \ln \left(1 - |\Gamma|^2 \right) \tag{11}$$

where $|\Gamma| = \left(\frac{\alpha^2 + (\beta - \beta_0)^2}{\alpha^2 + (\beta + \beta_0)^2} \right)$ - reflection coefficient modulus.

Formula (11) describes the relationship between the output values of the microwave moisture meter and the electrophysical parameters of the material. In addition to attenuation, the phase shift of an electromagnetic wave in a wet grain can be selected as a conversion parameter:



$$\Delta\varphi = \beta d,$$

where β - is the phase factor.

The phase factor for all materials is determined by the following formula:

$$\beta = \frac{2\pi}{\lambda} \sqrt{\frac{\mu \varepsilon'}{2} (\sqrt{1 + tg^2 \delta} - 1)}$$

In phase methods for measuring moisture content, the dependence of the phase incursion in the material on its moisture content is realized. When deriving relationships for the phase method, it is necessary to take into account phase incursions on all three components of the model (moisture, dry matter, and air). With this in mind, we write

$$\Delta\varphi = \left\{ \left[\beta_e + \kappa_t (t - t_0) \right] \rho'_H W + \beta_c \frac{\rho'_H (1 - W)}{\rho'_c} + 0,477 \beta_0 \right\} d + \varphi_0 \tag{12}$$

where φ_0 is the initial phase shift in the absence of material, depending on the design of the transducer and the geometry of the sample; κ_t is the temperature coefficient of the phase.

The φ_0 compensation can be performed by introducing an auxiliary phase shifter into the reference channel, when using a two-channel scheme, or it can be taken into account during the final calibration of the measuring transducer.

The most promising in microwave moisture metering is the combined amplitude-phase method for measuring humidity, especially when considering issues of increasing sensitivity, as well as when measuring in a narrow range. This method is based on simultaneous measurement of two parameters: attenuation - N and phase shift - $\Delta\varphi$ microwave wave.

And in this case, also in accordance with the accepted model, the wet material is represented as consisting of three flat layers: water, dry matter and air with a sufficient geometric size to neglect the edge effects. Then the equation for the quantities α and β will be written in the following form:

$$\begin{aligned} \alpha &= \alpha_w Q + \alpha_d V_d + \alpha_0 V_0 \\ \beta &= \beta_w Q + \beta_d V_d + \beta_0 V_0 \end{aligned} \tag{13}$$

where α and β are the attenuation coefficients and phases of the electromagnetic wave of the wet grain.

Taking into account that $\alpha_w Q$ is more than two orders of magnitude larger than the other terms [5-7] and introducing the constraint equations

$$Q = \rho'_H W; V_d = \frac{\rho'_H - Q}{\rho'_d}; V_w + V_d + V_0 = 1;$$

where $\rho'_H = \frac{\rho_H}{\rho_w}; \rho'_c = \frac{\rho_d}{\rho_w};$

we obtain the system of equations

$$\begin{cases} \alpha = \alpha_w Q \\ \beta = \beta_w Q + \beta_d \frac{\rho'_H - Q}{\rho'_{dH}} + \beta_0 V_0 \\ Q = \rho'_H W \end{cases} \tag{14}$$

The solution of this system with respect to W will have the form



$$W = \frac{1}{1 - \frac{\rho'_{dH}}{\beta_{dd}} \left[\beta_w - (\beta - \beta_0 V_0) \frac{\alpha_w}{\alpha} \right]} \tag{15}$$

The volumetric air concentration V_0 entering the equation can be determine from the ratio

$$V_0 = \frac{\rho' - \rho'_H}{\rho'} \quad (\text{where } \rho'_H = \frac{\rho_H}{\rho_w} - \text{natural weight}).$$

The dependence $\rho(W)$ and $\rho_w(W)$ for different types of grain is given in [6-9]. Comparing the results of calculating V_0 from these sources and with our data (Table 1), we can conclude that V_0 has a weak dependence on humidity in the range of 6 ... 26%. Only a slight increase in its value is observed at $W > 16\%$. Average value $V_{0\text{ av.}} = 0.472$ with a deviation from the average of no more than 4%.

Thus, $\beta_0 V_0$ in equation (15) can be taken as const and the moisture content of the material is quite unambiguously determined by the attenuation coefficients α and phase β , since the other quantities ρ'_{dH} , α_w , β_w and β_d are known.

Table 1. Dependence of natural weight, grain density and free volume on wheat moisture

W, %	8	10	12	14	16	18	20	22	24
$\rho_n, \text{g/cm}^3$	0,77	0,77	0,76	0,75	0,735	0,72	0,7	0,68	0,67
$\rho, \text{g/cm}^3$	1,43	1,42	1,4	1,39	1,37	1,36	1,34	1,32	1,3
V_0	0,45	0,456	0,458	0,46	0,464	0,471	0,478	0,485	0,495

V. CONCLUSION

The implementation of this conversion function, obtained on the basis of a layered model of the interaction of a microwave electromagnetic wave with a wet grain, provides great advantages when measuring in production, but it should be noted that the automatic measurement of two parameters α and β at microwave is a rather difficult task.

The performed theoretical studies show that for most cases of practical moisture measurement, when measuring grain moisture, the amplitude method should be recognized as the most acceptable, and for more accurate measurements in laboratory conditions, the combined amplitude-phase method.

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