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To cite this article: P I Kalandarov *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **939** 012091

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Study on microwave moisture measurement of grain crops

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Abstract. This article discusses the possibility of implementing the microwave method for controlling the moisture content of agro-industrial products, which allows it to be used to control technological processes in grain processing industries and to control materials in free space, converting the parameters of waves passed through the material's wave into an electrical signal. A functional diagram of the developed moisture meter is proposed, on the basis of the method, its electrodynamic characteristics are determined. Experimental data was obtained for samples of cotton seeds with specified moisture values. A method for measuring grain moisture in continuous production have been proposed, which gives a possibility to reduce the components of the measurement error caused by the uneven distribution of moisture in the grain, the inhomogeneity of the material in terms of density and temperature.

1. Introduction

Microwave moisture meters use a significant difference in the dielectric properties of water and dry material [1, 2]. The amount of moisture is measured by the attenuation of microwave radiation passing through the layer of the test material [3, 4]. In such moisture meters, the investigated object is located between the transmitting and receiving antennas. The transmitting antenna is connected to the microwave generator; the receiving antenna is connected to the measuring device. The higher the moisture contents of the analyzed material, the lower the signal that enters the measuring device [5]. The capabilities of microwave moisture meters to measure humidity in a wide range from 0 to 100% with higher accuracy. There are four known classifications of microwave methods: waveguide, resonator, probe and free space [6, 7]. In the system of grain products, the latter is most common. The informative parameters of the primary transducer are most often the amplitude, less often the phase of the transmitted or reflected wave. The basis of this method is the dependence of the attenuation of microwave energy on humidity. The following methods are distinguished in particular: amplitude and phase methods of moisture measurement. Distinctive features of these methods are: the amplitude method allows obtaining high accuracy in determining the moisture content, subject to stabilization or taking into account the temperature and grade of the material [8]. The phase method for measuring moisture, the dependence of the phase shift of the microwave wave on the moisture content of the material is the basic one [9, 10].

2. Materials and Methods

Consider the microwave method, cotton seeds, grain - wheat were taken as the object of measurement. In the microwave range, primary measuring transducers are electromagnetic systems with distributed parameters and, although the operation of microwave moisture meters is based on the dielectric method, the principles of their construction and operation differ significantly from the principles of construction



and operation from other analog methods, such as high-frequency moisture meters of the long range, medium and short waves, in which the primary converters can be considered as systems with lumped parameters. It is known [11] that electromagnetic waves pass through the entire layer of the material, due to which it is possible to measure the moisture averaged over the entire volume of the material. The moisture control of grain transported along the carrier can be measured according to the principle of the passage of an electromagnetic wave with a remote location of the antennas. The measured moisture is characterized by the power of the electromagnetic wave transmitted through the grain products, which are compared with similar characteristics of the probing wave. Resonant sensors provide a large area of interaction with grain material in the flow and, therefore, a high sensitivity. The collection of information is carried out covering the entire flow section of the measured medium at the measuring section, i.e., the characteristics of the received wave are averaged. The choice of the microwave method is based on the following considerations: measurement is non-contact and in large volumes, while the device has good metrological characteristics. Furthermore, fast results suitable for measurements in production lines, high accuracy of results, measurement does not depend on product density or product load, there is no influence of optical factors on the measurement, such as color change, product surface structure, moisture measurement on the product surface and in the center, non-destructive measurement method, no consumables such as reagents, etc., the devices do not require maintenance and are easy to use.

3. Theoretical Background

Grain crops are capillary-porous bodies by their structure. This structure is characterized by chemically bound moisture $W = 5 \dots 15\%$, which sharply differs in its properties from free water. It cannot be removed by drying or spinning. The dielectric permittivity of free space $\epsilon_{free} = 80 \dots 81$, while the relation has $\epsilon_{cons} = 2 \dots 5$, which differs little from the dielectric constant of the dry residue. The frequency dependence of the complex dielectric constant of a dielectric with one relaxation time is described by the equation [12]:

$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} \quad (1)$$

here ϵ_s and ϵ_∞ value respectively at $\omega = 0$ also $\omega \rightarrow \infty$; τ – relaxation time

As the frequency increases from ω_s to ω_∞ , the dielectric constant passes through the region of anomalous dispersion, in which the ϵ'' maximum, at the relaxation frequency is $\omega_\tau = 1/\tau$. This leads to a high sensitivity of the parameters of the electromagnetic wave to moisture contained in the material and low to other parameters of the material. Differences in the electromagnetic properties of the material and the medium in which the wave propagates, determines the reflected wave and the power of the transmitted wave:

$$\Phi_{incident} = \Phi_{reflected} + \Phi_{transmitted} \quad (2)$$

here: Φ - the power of the incident, transmitted and reflected waves.

The attenuation characterizing the loss of microwave power will be a function of the electromagnetic properties of the material, which determine the values of propagation constant

$$\gamma = \alpha + j\beta, \quad (3)$$

here: α – attenuation constant; β -phase constant

Most microwave moisture meters use the measurement of humidity by the absorption of microwave energy (attenuation). The measured parameter is attenuation A (dB), which in the case of sufficiently large layer thicknesses, when the reflection from the back wall can be neglected, is related to humidity by an approximate relationship [12].

$$A = 8,68\alpha_0 W \rho k D + |R|$$

Attenuation coefficient for water (db/m)

$$\alpha_0 = \frac{2\pi}{\lambda} \left[\frac{1}{2} \epsilon' (\sqrt{1 + tg^2 \delta} - 1) \right]^{1/2} \quad (4)$$

To consider α_e , ε' and ε'' , db/m)

ρ – wet material density, kg/m³; k – empirical constant, m³/kg;

D – material thickness, m; R – modulus of the reflection coefficient of the interface air – material.

In [13], it is proposed to increase the sensitivity of the method by measuring the attenuation at two values of D selected from the condition

$$D1 - D2 = \frac{\pi (2k - 1)}{(\beta_e - \beta_o)}; k = 1, 2, \dots, \quad (5)$$

where the index "0" refers to free space;

$$\beta_e = \frac{2\pi}{\lambda} \left[\frac{1}{2} \varepsilon' (\sqrt{1 + tg^2 \delta} + 1) \right]^{1/2} \quad (6)$$

here $tg \delta = \varepsilon'' / \varepsilon'$ - dielectric loss tangent;

$\varepsilon^* = \varepsilon' - j \varepsilon''$ - complex dielectric constant

λ - wavelength, m.

For homogeneous materials, when ε' and ε'' do not depend on the coordinate, the total phase shift of the wave passing through the material is:

$$\Delta \varphi = \left(\beta - \frac{2\pi}{\lambda} \right) D = \left[\sqrt{\frac{\varepsilon'}{2} (1 + \sqrt{1 + tg^2 \delta} - 1)} \right] D \quad (7)$$

At a constant sample thickness, D is uniquely related to moisture.

In the material, the power attenuation is described by an exponential law (Figure q):

$$\Phi_{incident} = \Phi_{reflected} e^{v l}$$

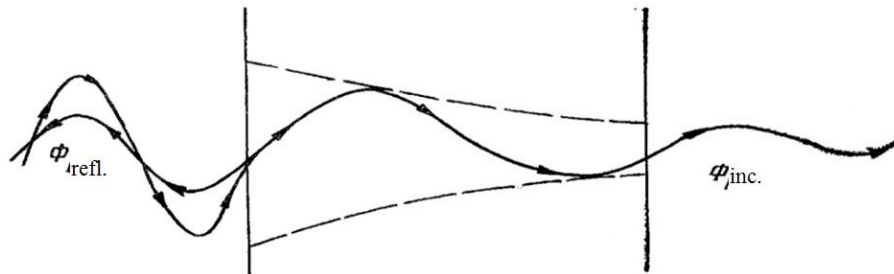


Figure 1. Scheme of interaction of microwave energy flow with wet material

At normal incidence and no reflection from the back surface ($D \gg \lambda$ and the attenuation are large), the modulus of the reflection coefficient $|R|$ is related to ε' and ε'' of the material by the dependence [14]:

$$R = (1 - \sqrt{\varepsilon' - j\varepsilon''})^2 / (1 + \sqrt{\varepsilon' - j\varepsilon''})^2;$$

at full reflection from a given sample surface attenuation

$$A = 8,65(2\pi/\lambda)\sqrt{\varepsilon'} D tg \delta$$

4. Results and Discussions

According to the methodology given in [12] and in accordance with the recommendations [13, 14], we have developed a microwave moisture meter [15, 16, 17] intended for use in systems for controlling grain technological processes by moisture in production conditions. Figure 2 presents the functional diagram and the principle of operation of the microwave moisture meter.

The advantage of the microwave method is its insignificant sensitivity to the physical and mechanical properties of the substances and materials under study, which makes it possible to analyze media without large active losses. Also, a noticeable advantage in the accuracy of the SHF methods over HF methods remains. However, the implementation of microwave moisture meters is much more complicated in

comparison with high-frequency moisture meters, because it is much more difficult to generate a microwave electric field of sufficient power than an HF field. The method based on the physics of properties in microwave electromagnetic fields is equal to the frequency range from 5.107 to 5.1010 Hz. [18]. This is due to the fact that, with increasing frequency, the sensitivity of the measuring device increases and the influence of uninformative parameters decrease.

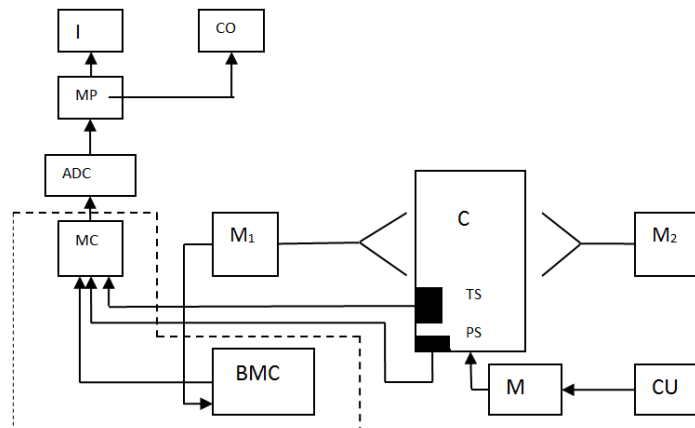


Figure 2. Structural diagram of a microwave moisture meter

The moisture meter is built on a block-modular basis. The cuvette (C) with the sample is rotated around the vertical axis by a stepping motor (M), which is controlled by a control unit (CU). Signals from M1 and M2 (microwave modules) and temperature (TS) and pressure (PS) sensors are fed to the basic measuring circuit (BMC), here signals of attenuation, microwave phase shift, temperature and pressure of the sample are formed into standard signals for interfacing with a micro-controller (MC), from which the signal corresponding to the measured value is fed to the analog-to-digital converter (ADC).

A microprocessor (MP) performs all computational operations. After calculating the polynomial, the moisture content of the material is determined and digitally displayed on the indicator (I) and fed to the control object (CO) regulation. Of the moisture measurement methods used in industry, only high-frequency moisture measurement can compete in terms of the breadth of use with the microwave method [19]. The advantages of microwave moisture measurement are: the possibility of contactless measurement, the relative simplicity and low cost of the equipment, and in some cases, good metrological characteristics. The difference between high-frequency and microwave methods is caused both by the commensurability of the wavelength with the minimum characteristic dimensions of the object, and by the peculiarity of the behavior of bound water in the gigahertz range [20]. Thus, as can be seen from this analysis devoted to the study of measuring the moisture content of grain materials, as well as on the basis of studies [21, 22], the most promising method for solid free-flowing dispersed grains and grain crops is the microwave method. The structural comparative analysis of many schemes of microwave moisture meters is described in more detail in [23]. Figure 3 shows a graph of the dependence obtained experimentally, for cotton seeds, with the following parameters: moisture characteristics on samples of cotton seeds of the third grade, medium fiber variety, pubescence of 11%, and weediness of corp 5%, with a moisture content of 8.7%, all were prepared and 38 samples were tested with humidity from 3.5 to 20.3% and density - 367.3 kg / m³. After checking the homogeneity of the dispersion, the values of the variance of reproducibility were calculated, which are equal to:

$$\sigma_A^2 = 0.14Db^2.$$

The processing of the experimental results showed that the moisture content of seeds is adequately described by polynomials of the second degree.

$$A = 0,55W^2 - 0.116 + 1.742 Db.$$

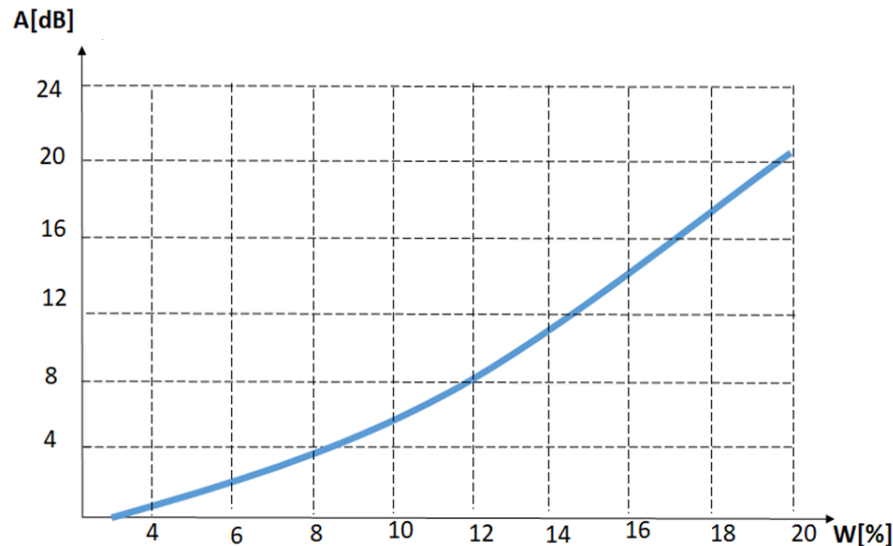


Figure 3. A graph of the dependence of the attenuation of microwave energy on the moisture content of cotton seeds

The study of the influence of non-informative parameters was carried out on the materials under consideration, since they are the most complex in their structure and as an object of measurement is of greatest interest differing from other cereal products by some specific properties, where the density of the samples varied within $340, \text{ kg / m}^3 - 420.0 \text{ kg / m}^3$, and the temperature is from 10 to $50 \text{ }^\circ\text{C}$, which covers the entire range of possible changes in density and temperature in real conditions. The dependence of attenuation on density was described by an equation of the first degree, and the temperature also turned out to be linear in the selected range of humidity temperatures, which is confirmed by theoretical considerations on the linearity of the dependence of attenuation, the results of phase attenuation are not presented in this article. For communication of the moisture meter with a computer of a higher hierarchy, an external device interface is provided. The use of modern element base and microprocessor technology has contributed to the improvement of the metro-logical characteristics of the moisture meter and the expansion of the scope of its application.

The equation at a confidence level of 0.95 adequately describes the results of the experiment. The moisture meter can operate both autonomously and as part of an automated process control system [24, 25].

Based on the literature analysis of many authors in the field of microwave moisture measurement [26-30], it is recommended to conduct research and measure the materials under study at a temperature of $365-375 \text{ K}$ in order to expand the applicability of the method in the field of low moisture content, and the choice of the operating frequency is a compromise solution, the transition to shorter waves increases the sensitivity of the moisture meter; however, at the same time, the area of the investigated sample decrease, the complexity and cost of the equipment grow respectively. While, the use of longer waves worsens the metro-logical properties of the moisture meter (sensitivity, error due to changes in the composition of the material), enlarges the mass and dimensions of the device. The main disadvantage of microwave moisture meters is the dependence of the density on the thickness of the layer of the material under study. However, in our studies, the material moisture and the influencing quantities change simultaneously. Therefore, it is an interesting mathematical model of the primary transducer of the measuring device that affects the joint influences and the main influencing quantities on the output signal of the primary transducer of the methods are multi-factor experiment, development of software for the microprocessor of the measuring device, in particular, for automatic compensation of errors from the main influencing quantities of density and temperature.

5. Conclusions

In this work, the analysis of moisture metering methods was carried out. The theoretical foundations of microwave moisture measurement are considered, a resonator sensor of the amplitude measuring device is developed. The proposed scheme of the sensor design makes it possible to quickly fill it with a controlled sample, and also measure the electrodynamic characteristics of the developed transducer. The analysis of the physical and chemical processes of the interaction of moisture with the material under study, the existing technological processes of drying and methods of moisture control led to the conclusion that the dielectric control method has the greatest functionality, which can be implemented by various options for devices with digital information processing. When developing such a device, the main purpose was to apply it in the field, during harvesting various solid, free-flowing products of the agricultural sector. Results of approbation of this device let us implement it as a prototype model and develop on its basis in the future a device based on the amplitude microwave method [31]. Creation on the basis of this method of microwave moisture meters, capable of operating in difficult conditions, where control and regulation of humidity must be ensured at all stages, from the preparation of raw materials to storage and shipment of finished products is one of the urgent tasks in the moisture metering area [32]. Recent research shows that the relation of the dielectric properties of grain and grain crops on their moisture content in the microwave range have the same form and are much close to each other. In this approach is intended for field measurements of the moisture content of agricultural crops, when it is necessary to rapidly and accurately obtain reliable results. These circumstances make it possible, on the basis of the constructed device, to create a universal microwave moisture meter for grain crops [33].

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