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PHYSICOCHEMICAL MEASUREMENTS

HIGH-FREQUENCY MOISTURE METER FOR MEASURING THE MOISTURE CONTENT OF GRAIN AND GRAIN PRODUCTS

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This work investigated the technical aspects of the construction of devices for measuring the moisture content of grain and products of the agro-industrial complex. The necessity of developing primary moisture measuring transducers has been substantiated. The dielcometric method for determining the moisture content, based on the dependence of the dielectric permittivity of a controlled material on its moisture content, was considered. The dependencies linking the electrophysical parameters of materials with moisture content and uninformative parameters of materials were examined. A structural diagram of a high-frequency (HF) moisture meter is presented, whose operation principle is based on the dielcometric method of measuring the moisture content of materials. A prototype of a grain moisture control device was developed, which comprises a primary measuring transducer in the form of a two-link system with two input parameters (output signals of the humidity sensor) and the active component of the output signal. The proposed HF moisture meter can be used to measure the moisture content of grain and grain products in industrial and laboratory conditions.

Keywords: *moisture content, primary measuring transducers, moisture meter, electrophysical characteristics, control methods, informative parameters, non-informative parameters, dielectric permittivity, electrical conductivity.*

Introduction. The technical level of economic outputs and the aspects of the use of material, energy, and labor resources depend on the quality of control-gauging instruments. Grain-processing enterprises receive heterogeneous batches of grain. To increase the efficiency of agro-industrial complex (AIC) enterprises, scientists have developed and introduced measuring instruments and automated production management systems of production processes. In particular, for grain-processing enterprises, devices (moisture meters) have been created to determine the moisture content of grain and grain products using an express method [1].

Various methods and devices can be used for determining the moisture content of materials [2–11]. In the global practice, dielcometric high-frequency (HF) moisture meters are commonly used, whose capacitive primary transducer contains the material under study [12–15]. General technical requirements (GOST 29027-91, “Interstate standard. Moisture meters of solid and bulk substances. General technical requirements and test methods”) have been established for moisture meters and methods of their testing.

Under the supervision of the author of this article, a group of scientists from the National Research University Tashkent Institute of Irrigation and Agricultural Mechanization Engineers has been conducting research for the past few years to improve the metrological characteristics of a series of measuring devices for grain products. As a result of their work, primary measuring transducers of the electrophysical parameters of grain products were proposed, the functional diagrams

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of the indicated devices were justified, and the engineering calculation methods of the characteristics of the transducers were developed [16–18].

This work aimed to develop a dielcometric HF moisture meter on the basis of a primary measuring transducer (sensor) of moisture content for the measurement of the moisture content of grain and grain products.

Dielcometric method for determining the moisture content. The dielcometric method for determining the moisture content of AIC materials is based on the dependence of the dielectric permeability of the materials on their moisture content [2, 19]. Based on the dielcometric method, moisture meters have been developed to measure the moisture content of grain and other materials [20, 21, 3].

The disadvantage of dielcometric moisture meters is a low sensitivity to changes in electroconductibility, depending on the operating frequency of a moisture meter [4]. The dielcometric method is used in medium- and shortwave (0.3–30 MHz) frequency ranges and in the ultra-HF range [22]. There is also an intermediate frequency range with a frequency of approximately 100 MHz, which is the highest for systems. The geometric dimensions of sensors and other elements of measuring circuits are much less than the shortwave band wavelength, so these sensors can be considered systems with distributed parameters. To increase the sensitivity of moisture meters to changes in electrical conductivity, researchers have selected a frequency of approximately 30 MHz.

There are two aspects of the output signal transformation of dielcometric primary HF transducers (sensors). First, the output signal always has a comprehensive nature; that is, the complete resistance of the primary measuring converter with the material is a complex value. The reactive (capacitive) component of this resistance is associated with dielectric permeability, and the active component is associated with dielectric and conductivity losses. Second, the dielectric parameters of wet materials depend on the frequency of the electromagnetic field. This is due to the frequency dependence of various polarization types. Structural (intra-layer) polarization is mainly manifested at low frequencies, but the microinhomogeneity of materials can affect the dielectric permeability at high frequencies. An increase in the material polarization capacity increases its dielectric permeability. With an increase in the frequency, the total polarization is reduced due to inertia and other factors. The resulting polarization is determined by the sum of all types of polarization available in this material.

The AIC products belong to the class of heterogeneous systems owing to their multicomponent and heterogeneous structure. The aspects of heterogeneous mixtures are taken into account during the mathematical description of the electrical properties and dependence of the dielectric properties of the studied materials on their moisture content [15, 23, 24].

An increase in the material moisture content reduces its resistance, which is equivalent to the transition of the material into the semiconductor state, and the electrical conductivity of grain materials increases. The electrical properties of the sample change nonlinearly with an increase in its moisture content [25]. Many products become greasy during processing. The admixture of salt dramatically increases active losses, and conductivity becomes ion in nature.

The dependence of the electrical conductivity γ of grain on the moisture content W is determined by the following equation:

$$\gamma = a\exp(bW) + C,$$

where a and b are the constant coefficients for this sample, and C is the constant capacity of the measuring circuit.

A dielcometric HF moisture meter is presented in the form of a two-sequent system with two input parameters R and C (output signals of a moisture content sensor) and the active component of the output signal Y.

The nominal static characteristics of the measuring device transformation of moisture meters are calculated according to the following equation:

$$Y = f(Y_{\text{in}}),$$

where Y and Y_{in} are the output (readings) and input signals of the measuring device of the moisture meter, respectively.

Y_1, Y_2, and Y_3 were obtained through measurements of various moisture values W_1, W_2, and W_3, respectively. Due to the measurement errors Δ_i the value of Y_i differs from the true value $f(W_i)$ with $Y_i = f(W_i) + \Delta_i$.

The moisture content measurement of grain materials with capacitive moisture meters is based on a linear dependence of the output signals of the primary measuring converter of the moisture meter on the moisture content and various influencing factors (interference) [26], including temperature T, degrees of heterogeneity S, maturity Z, and grain storage and processing conditions U.

The change in the output signal Y is described with the following equation:

$$dY = \frac{dY}{dW}dW + \frac{dY}{dT}dT + \frac{dY}{dZ}dZ + \frac{dY}{dU}dU. \tag{1}$$

The first term of Eq. (1) determines the sensitivity of the measured parameters to moisture, and the rest of the terms determine errors caused by a change in factors.

The moisture content measurement depends on the way the moisture metric system as a whole and the primary transducer of the moisture meter ensure the fulfillment of conditions [5, 7]

$$\frac{dY}{dW} \to \max; \quad \sum\left(\frac{dY}{dZ}; \frac{dY}{dT}; \frac{dY}{dU}\right) \to \min.$$

Error minimization is achieved, provided that the sensitivity of the measuring device to changes in the moisture content $S_W = dY/dW$ is maximum, and the sensitivity to interference $S_{\mathrm{i}} = dY/dZ + dY/dT + dY/dU$ is minimal [8].

HF moisture meter for measuring grain moisture. This article offers a technical solution to the primary transducer design. A capacitive-type measuring cell is a vessel with metal electrodes. The controlled material is placed in a capacitance transducer, to which the HF voltage of the measuring generator is supplied. As a result, the parameter of the dielectric permeability corresponding to the moisture content of the controlled material is determined.

The measurement object is not the dielectric permeability of the studied material but the capacity of the measuring sensor. The capacity of the primary transducer filled with the controlled material is the function of many parameters [27]. The wet material represents a complex multicomponent system, whose dielectric characteristics are determined by the ratio of various forms of moisture linkage. There is no mathematical expression of the dependence between the quantitative content of water in the material and its dielectric characteristics. Therefore, it is necessary to experimentally determine the dependence, that is, to empirically reveal the calibration characteristic of the moisture meter.

No product can be considered an ideal dielectric, so the electrical energy supplied to the condensing transducer filled with the product is not only consumed on the reloading of the capacitor but also dissipated in the form of thermal losses in the dielectric [25, 26]. The equivalent diagram of the transducer filled with the analyzed material can be represented in the form of an electric circuit [28].

The functional dependence of the dielectric characteristics of the material on its moisture content can formally be considered primary transformation. The output signal of the primary measuring transducer is a useful output signal of the measuring device [5, 28].

Previously published works [5, 28, 29] present a replacement diagram of the dielectric transducer, containing a geometric capacity (container corresponding to the electrode field in vacuum) and the sum of containers dependent on the polarization of various types. For the specified scheme, the transducer variable capacity C_k corresponding to the moisture content of the measured material is determined according to Refs. [5, 24, 30] as follows:

$$C_k = C\left[\left(1 + \frac{r'_n}{r'_m}\right)^2 + \frac{1}{\omega^2 r'_m C^2}\right], \tag{2}$$

where C is the capacity of the reference generator, relative to which the dielectric permeability of the sensor is measured; r'_m is the equivalent resistance of conductivity losses; r'_n is the equivalent resistance of polarization losses; and ω is the circular frequency.

Equation (2) shows that the actually measured variable capacity C_k with the same moisture content significantly varies due to changes in the material conductivity. Therefore, it is necessary to compensate for the influence of active losses on the measurement result.

The nature of the electromagnetic field interaction with moist materials is determined by the values of complex dielectric and magnetic permeability. In this case, the polarization phenomenon should be taken into account. There are four types of polarization (electronic, atomic, orientation, and voluminous). In the electromagnetic field, energy losses are accompanied to the polarization of all types. Polarization capacity is a complex value, and it shows resonance properties. That is, for the polarization of each species, there is a certain frequency range, where losses are maximum.

The water molecule, even without an external electric field, has a dipole moment due to the location of O–H bridges at an angle of 105°. In this regard, the water molecule, which is in a variable magnetic field, begins to fluctuate, turning round along the power lines (dipole polarization), which leads to the absorption of an electromagnetic pulse by the molecule [19].

When measuring moisture content, the following pairs of values are used:

– actual ε' and imaginary ε'' components of a complex dielectric permeability $\varepsilon^* = \varepsilon' - j\varepsilon''$;

– dielectric permeability ε and tangent of the angle of dielectric loss $\tan\delta$;

– dielectric permeability ε and specific conductivity (precisely, its active component) σ.

Dependencies between the complex permeability and conductivity are as follows:

$$\varepsilon' = \varepsilon; \quad \varepsilon'' = \sigma/\omega; \quad \tan\delta = \varepsilon''/\varepsilon' = \sigma/(\omega\varepsilon'); \quad \varepsilon^* = \varepsilon(1 - j\tan\delta).$$

By knowing one of these parameters, we can calculate any other pair.

The processes occurring in dielectrics in an electric field can be described with complex dielectric permeability [6]:

$$\varepsilon^* - \varepsilon_\infty = (\varepsilon_0 - \varepsilon_\infty)/(1 + j\omega\tau), \tag{3}$$

where τ is the relaxation time.

We single out the actual and imaginary components of dielectric permeability from Eq. (3). Relative dielectric permeability is calculated using the following equation:

$$\varepsilon' = \varepsilon_\infty + (\varepsilon_0 - \varepsilon_\infty)/(1 + j\omega\tau). \tag{4}$$

The coefficient of dielectric losses (the degree of energy absorption in the substance placed into the electric field) is defined as follows:

$$\varepsilon'' = (\varepsilon_0 - \varepsilon_\infty)\omega\tau/(1 + \omega^2\tau^2).$$

From Eq. (4), we calculate the maximum value of the imaginary component of dielectric permeability:

$$\varepsilon''_{\max} = (\varepsilon_0 - \varepsilon_\infty)/2.$$

The actual and imaginary parts of dielectric losses are the functions of the attached field, calculated through the tangent of the angle of dielectric losses, and also depend on the frequency ω. With an increase in ω, when the period of the alternating electric field is commensurate with the relaxation time, the actual component of dielectric permeability decreases [8].

In the low-frequency area, the cophased following of a dipole after an electric field is disturbed. In the HF field, oriented polarization disappears, and only the slowly changing polarization of the shift remains.

Design and principle of the operation of the HF moisture meter. Figure 1 presents a functional diagram of the HF moisture meter developed and proposed in this article. This meter is designed to measure the moisture content of the grain and its processing products.

The HF moisture meter structurally consists of a sensor and two electronic blocks of a measuring-transforming pathway with a sample-forming manipulator. The primary capacitive converter is connected to the entrance of the measuring HF generator. The sensor electrodes are made of durable titanium material and coaxially pressed into the lower part of the electric ceramic structure. To prevent sticking of the moist material on the sole and electrodes, the sensor is equipped with an electric heater. A steel basis comprises grooves for the placement of the heating element.

The HF capacitive moisture meter of bulk materials works as follows: Through the capacitive primary transducer *1*, the material (grain legume crops) is passed, with the changing moisture content. In this case, the material dielectric permeability and, therefore, the electrical capacity of the primary transducer change. Accordingly, the frequency of the measuring HF generator *2* changes as the primary transducer is included in its oscillatory circuit. From the measuring HF generator output, the HF signal enters the input of the signal formation block *3*, at the output of which the signal has a rectangular shape. The pulse frequency is equal to the frequency of the measuring HF generator. The signal specified enters the entrance 1 of the arithmetic converter block *4*.

A reference HF generator *10* assembled from elements identical to the elements of the measuring HF generator *2* sends a signal of a constant (support) frequency to the input of the signal formation block *11*. This is equal to the frequency of the measuring HF generator in the event of a zero moisture content value of the controlled component. The signal of the

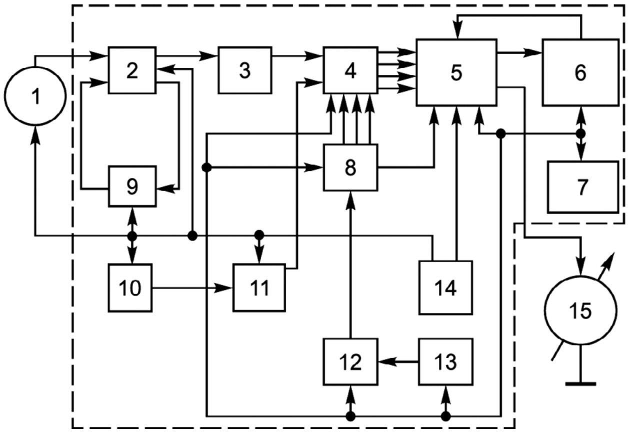

Fig. 1. Functional diagram of an HF capacitive moisture meter for granular materials: *1*) sensor; *2*) measuring HF generator; *3*) shaper of measuring signals; *4*) arithmetic converter; *5*) digital-to-analog converter; *6*) analog-to-digital converter; *7*) digital display; *8*) signal distributor; *9*) active loss stabilizer; *10*) reference HF generator; *11*) shaper of reference signals; *12*) frequency demultiplier; *13*) clock generator; *14*) power supply; *15*) self-recording device.

reference HF generator in the signal formation block *11* is subjected to the same processing as the signal of the measuring HF generator in the signal formation block *3*. Thus, the signal of the reference HF generator in the form of rectangular pulses enters from the signal formation block *11* to the input 2 of the arithmetic converter block.

Rectangular infralow frequency impulses of the order of 1 Hz of the outputs 1, 2, and 3 of the block *8* sequentially enter the control inputs 3, 4, and 5 of the arithmetic converter block at regular intervals. Block *8* of the signal distribution is connected through the frequency demultiplier *12* with a clock generator *13*. Blocks *8*, *12*, and *13* of the device are used as an electronic switch.

The arithmetic converter is located on reciprocal counters. The signal distributor switches the circuits, zeros the reciprocal counters, records the frequency of the reference signal, records the frequency of signals of the measuring channel, and records the frequency difference in the digital-to-analog converter (DAC) *5*.

The result obtained is proportional to the controlled parameter. After a pause corresponding to the algorithm of the moisture meter system, the DAC impulse is received from the signal distributor to the control input of the arithmetic converter block, allowing the indication and recording on the self-recording device *15*. The analog-to-digital converter *6* signal is simultaneously indicated on the digital display *7*, where the moisture content value is recorded and remembered until the next counting. The indication of the output information on a digital display is a quantitative measure of the controlled component of the material. The power supply block *14* is grounded by a common bus.

The work cycle of a capacitive HF moisture meter is repeated in the above sequence.

Considering that this device is pilot and its metrological maintenance as a measuring instrument is not intended for official use in the field of state regulation and ensuring the uniformity of measurements, the developers of the proposed HF moisture meter for grain and grain products calibrated and graduated the device through a voluntary verification in accordance with the methodology presented in [31, 32].

The device can be operated in laboratory and experimental–industrial conditions. To compensate for the effect of temperatures, the heating resistor is used, designed for a temperature of up to 60°C.

Metrological characteristics of the device

Measurement range	8.0–18.5%
Limit of the permissible values of the main error	0.8% (n)
Operating temperature range	–5 to +50°C
Sample weight	100 g
Setting time	10 s
Operating mode	Discrete–continuous
Output analog signal	4–20 mA
Output interface type	Modbus RTU

The device proposed in this article can be successfully adapted to determine the moisture content in various agricultural products. After the state certification, the developed device can be used in any manufacturing environment.

Research results. The results of the use of the proposed moisture meter were compared with data obtained by the standard method (drying) in industrial laboratory conditions. For a batch of 10 samples of wheat grain, the moisture content was 13–13.5%, and the average moisture content was 13.25%. The error of the standard method was within 0.5% (n). When measuring the similar samples using the proposed moisture meter, the average moisture content turned out to be 13.35% with an acceptable error of 0.7% (n). The deviation from the average moisture content value was 0.1%, and the difference in error was within ±0.2% (n). Thus, the accuracy of the proposed moisture meter was recognized as satisfactory by the operating services of grain-processing enterprises.

Conclusion. The primary transducer developed by the author enabled to create a pilot sample of the dielcometric express HF moisture meter for grain products. The proposed device can measure the moisture content of the grain samples on the conveyor or screw for a long period of time without the deterioration of parameters with a minimum error of the measured dielectric permeability and therefore moisture content.

The main results of the moisture content measurements obtained using the developed device comply with the requirements of the operating services of grain-processing enterprises to ensure the rapidity and accuracy of the device.

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