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MATHEMATICAL MODEL OF A HIGH-FREQUENCY MOISTURE METE FORCOTTON SEEDS BASED ON SUBSTITUTION SCHEMES

O. N. Norboev
Karshi Institute of Engineering Economics
o.norboyev@mail.ru

S. U. Farxodov
Karshi Institute of Engineering Economics
s.farkhodov@mail.ru

M. N. Eshonqulov
Karshi Institute of Engineering Economics
G-mail.mansureshonqulov8@gmail.com,

B. Sh. Ibragimov
Karshi Institute of Engineering Economics
bekobod.1988@mail.ru

Annotation

An overview of high-frequency methods for measuring and controlling the moisture content of various materials is given. The moisture content of cotton seeds is the main factor affecting their quality and quantity indicators in the technological processes of storage, transportation, processing. Therefore, measuring the moisture content of cotton seeds directly in the technological process is an urgent task. A mathematical model of a high-frequency moisture meter for cotton seeds has been built, in which the material under study is presented in the form of a complex dielectric in an electric field. A substitution scheme is proposed, containing a capacitance between the electrodes, as well as resistance capacities corresponding to various types of polarization. Four variants of the equivalent circuit are considered, which approximately describe the dependence of the dielectric loss tangent on the frequency of the used electromagnetic field. It is shown that the simplest parallel two-element RC equivalent circuit most closely matches the real description of the measurement object in the frequency range 105– 108 Hz.

Keywords: replacement circuit, moisture, capacity, cotton seeds.

Introduction

The high-frequency method for measuring humidity is based on the dependence of dielectric parameters and knitted with them electrical quantities from the moisture content of the material. To measure humidity, the medium and long wavelength ranges (0.1– 50 MHz) of high frequencies are most often used. In the indicated ranges, the primary capacitive converters of dielcometric moisture meters can be considered as systems with lumped parameters. The use of the high-frequency method for measuring the moisture content of various materials is widely covered in the literature. In [1], to improve the accuracy of digital moisture meters used to measure the moisture content of various materials with increased electrical conductivity, a two-parameter control method was proposed. This method is based on measuring and comparing with the empty values of the amplitude and phase of the output signal of a measuring transducer with a capacitive sensor excited by a high-frequency signal.

In work [2] the characteristics of modern industrial thermogravimetric, dielectric, neutron and microwave moisture meters are given. In particular, dielectric-cometric moisture meters implement the dielectric (capacity-bone) principle of moisture measurement. When interacting with the analyzed material, the moisture meter sensor generates a signal proportional to the dielectric constant of the substance and then converted into a moisture value. Moisture meters of this type are characterized by average values of the accuracy of measuring the moisture content of materials, but they are compact, which makes it possible to control the change in the moisture content of materials in the field.

To increase the reliability of humidity control under conditions of increased active conductivity of the controlled material, it was proposed [3] to use a two-parameter method of resonant dielectric measurements. To implement this method, a device circuit has been developed and experimentally investigated, which makes it possible to significantly reduce the measurement error and power consumption.

In [4], a high-frequency method for measuring humidity is considered and variants of devices for monitoring the humidity of capacitive measuring transducers that implement this method are proposed. In order to reduce the influence of the instability of the design characteristics of the primary measuring transducer on its accuracy, a technique has been developed for the engineering calculation of the geometric dimensions and the working capacity of the transducer. A method for calculating capacitive transducers for measuring humidity based on recording the dielectric constant of the materials under consideration is proposed in [5]. Also, the

$$\varepsilon^* = \varepsilon_{Re} + i\varepsilon_{Im};$$
$$tg\delta = \varepsilon_{Im} / \varepsilon_{Re};$$
$$\sigma^* = \sigma_{Re} + i\sigma_{Im},$$

sizes of electrodes of capacitive transducers for controlled materials are selected.The approach used in this work made it possible to synthesize an electric capacitive model of the primary measuring transducer and its hardware implementation, which together provided an acceptable approximation of the real frequency-humidity characteristics in the high-frequency range.The main issues of obtaining measuring information about the parameters of technological processes, methods and principles of measurements, devices and schemes of moisture measuring instruments are described in detail in the manual [6]. The work [7] presents an overview of instruments for the quantitative determination of water in oil and oil products. The author of [8] managed to increase the measurement accuracy, simplify the device and its operation, reduce the measurement time, and expand the functionality of the device for measuring the moisture content of bulk materials. The theoretical foundations of the dielcometric method for measuring humidity are given in [9]. In [10], melon seeds were investigated and found that their electrical resistance, conductivity, dielectric constant, loss factor, loss tangent and capacitance very strongly depend on the humidity and frequency of the alternating electric field. In [11], a dielcometric method for measuring the surface area of cotton grains was proposed, its results were compared with the data obtained by other methods of measuring the area. Measurement of soil moisture by the method of frequency dielcometry is considered in [12]. This method is promising for measuring soil moisture in a long-term interval, as well as moisture flows during filtration failure and transport flows, where traditional measuring instruments have certain limitations. To obtain the frequency-humidity dielectric characteristics of forage grasses, an experimental laboratory setup based on a capacitive sensor is presented in [13], and an interval of operating frequencies for carrying out measuring work is determined.

It is known that the dielectric properties of any wet material are described by the complex dielectric constant [3], the tangent of the dielectric loss angle and the complex conductivity, respectively:

where **εRe, σRe, εIm, σIm** – real and imaginary components, respectively, of the dielectric constant and conductivity.

The purpose of this article is to build a mathematical model of a high-frequency moisture meter, with sufficient accuracy describing its conversion function and the function of the influence of basic quantities.

Construction of a mathematical model of a high-frequency moisture meter.

Almost any device for measuring the moisture content of bulk materials can be represented in the form of a generalized structural diagram based on any electrophysical, including dielcometric, moisture measurement method and consisting of three series-connected links.humidity w- in the physical (in this case, electrical) value e, that is, it describes the dependence of the electrical properties of the material used in this method on its moisture content. Link 2 is the primary measuring transducer (sensor) of the moisture meter, which converts the value e into an output signal x convenient for further processing (capacity, complex resistance, or one of its components). Link 3 describes a measuring transducer (measuring device), at the output of which an analog or digital signal y is received.

To describe the function of influence of uninformative parameters, it is necessary to take into account the interference affecting all links. For example, for link 1, such interference will be changes in temperature, density, chemical composition and other parameters of the material under study, affecting its dielectric characteristics, for link 2 - the shape and mass of the material, the frequency of the electric current and others that change the characteristics of the material. measuring device. The effect of the shape and mass of the material under study on the capacity of the used electrodes is related with the need to maintain a certain pressure when calibrating the measuring device.

For link 3, the interference will be mainly water in the materials under study, which subsequently can lead to the appearance of active conductivity between the electrodes, as well as to polarization effects. It is especially difficult to describe the conversion of moisture into dielectric properties (link 1) of natural moisture-containing materials, in particular, biological materials of plant origin, to which cotton seeds and their processing products belong. Such complex multicomponent and structurally heterogeneous materials such as cotton seeds belong to the class of heterogeneous systems. Therefore, when describing their electrical properties, along with the methods of modern physics of dielectrics, it is necessary to take into account the features of heterogeneous mixtures [14].

In an alternating electric field, the main process that determines the properties of a real dielectric is polarization. Almost all known types of polarization are observed in cotton seeds: electronic, ionic, dipole-relaxation, electrolytic and structural. The resulting polarization is determined by the sum of all polarizations present in a given material. Depending on the characteristics of the material, different types of polarizations are of greater or lesser importance. For example, for cotton and cotton materials, inertial types of polarization are dominant in the high frequency range: dipole-relaxation and structural.

In general, a complex dielectric in an electric field can be described by an equivalent circuit containing a capacitance between the electrodes in a vacuum C_0 and the sum of capacities corresponding to different types of polarization. In the equivalent circuit, there are also series resistances that take into account the energy loss during polarization. In addition, the circuit provides for an active resistance R, which characterizes the through conduction current between the electrodes. Two major features of the conversion of humidity into the output signal of a dielectric high-frequency primary converter follow from this equivalent circuit.

The first feature is associated with the fact that the output signal is always complex in nature, that is, the impedance of the primary measuring transducer with the material is a complex quantity. The reactive (capacitive) component of the resistance is related to the dielectric constant, and the active component is related to the dielectric losses and conductivity losses.

The second feature is due to the dependence of the dielectric parameters of the test material on the frequency of the used electromagnetic field in the device for measuring humidity. This is due to the frequency dependence of the polarization of various types. For example, structural (intra-layer) polarization manifests itself mainly at low frequencies, but if there are microinhomogeneities in the cotton components, then such polarization can also occur at high frequencies. With an increase in the degree of polarizability of the material, its dielectric constant also increases.

With increasing frequency, one can expect a decrease in the total polarization due to inertia and other effects, as well as a decrease in the value **εRe**.

The effect of frequency on the dielectric characteristics of heterogeneous moisture-containing systems is aggravated by a number of factors. Dielectric characteristics of a heterogeneous mixture (asand temperature characteristics) are very different from the characteristics of the individual components of the mixture. Due to the interaction between the dispersion medium and the dispersed phase, the dispersion region expands, and relaxation can occur not at one frequency, but in a wide part of the frequency spectrum. Sometimes even several highs can be observed ε_{Im}.

The effect of a double polarized layer of particles of a component system leads to the fact that a heterogeneous mixture (especially at low frequencies) can acquire a dielectric constant exceeding the value ε * of any component of the mixture, including water. The second influencing factor for conductive particles or inclusions is their shape. Also, in the systems under consideration, the form and the type of connection of moisture with dry matter.

Various mechanisms causing losses in heterogeneous systems in a wide range of frequencies are summarized in [15].

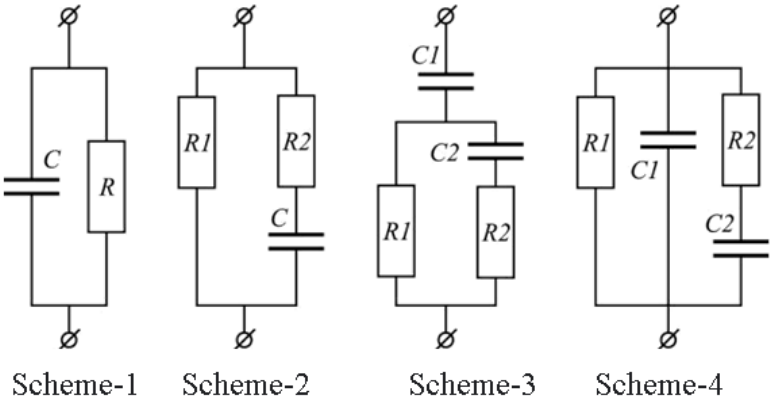
At low frequencies, losses are due to the superposition of a number of effects, the separation of which is very difficult. In the super-high-frequency (microwave) range, the picture is simplified: the main type of losses becomes relaxation losses associated with slowly establishing types of polarization. This, in particular, explains the minimization of errors associated with electrolytes (salts, acids) during measurements in the microwave range.in water, compared with measurements at lower frequencies, including in the high-frequency range.

Cotton seeds, which are a complex heterogeneous system, are distinguished by a high degree of structural heterogeneity. The total polarization in cotton seeds has a very wide, almost continuous spectrum of time for the establishment of various types of polarization.

Even in a simplified model of cotton seeds as a three-phase system of fiber, moisture and air, the dielectric properties of these components differ significantly. Water can be considered as an inclusion in a non-conductive and non-relaxing medium (dry core, shell, fluff and air). At the same time, moisture forms both large (a film on the surface of seeds, fluff, liquid water in large pores) and small (moisture in small pores of seeds, in the spaces between fibrils and mesceles) inclusions.

Equivalent circuits for investigating the dependence of electrical parameters on the frequency of the measuring device

With an increase in the moisture content of cotton seeds, moisture is distributed not in the form of separate scattered inclusions, but in the form of continuous films, bridges, etc. This results in a wide, almost continuous equivalent circuit. Let us choose four simplest variants of the equivalent circuit (Fig. 1), approximately corresponding to the characteristics considered in [15] tgδ(f). Before processing the experimental data, we analytically investigated the tanδ (f) dependence in the frequency range 104–107 Hz for all four equivalent circuits. For circuits 1, 3, 4, with increasing frequency, the tangent of the dielectric loss angle decreases monotonically, and for circuit 2 at low frequencies the tgδ values also monotonically decrease to a certain value fmin, and then increase. Thus, according to Scheme 2, the parameter tgδ has an extreme value.



Scheme-1 Scheme-2 Scheme-3 Scheme-4

Fig. 1. Typical RC equivalent circuits

Due to the fact that the real characteristics of cotton seeds and products of cotton, fat and oil production have no extremum [4], further scheme 2 was not considered.

For a more detailed comparison of the remaining three variants of the equivalent circuit, it is necessary to analyze the characteristics of each circuit for the minimum root mean square error:

$$\Delta=\sum_{i=1}^{n} g_i^2\left[y_i-\mathrm{tg}\delta(f_i, a, b, c)\right], \qquad (1)$$

where g_i is the weight function; y_i - ordinates of characteristics; a, b, c - approximating coefficients.

Coefficients a, b, c are determined from the conditions for minimizing errors:

$$\left.\begin{array}{l}\partial\Delta/\partial a=0;\\ \partial\Delta/\partial b=0;\\ \partial\Delta/\partial c=0.\end{array}\right\} \qquad (2)$$

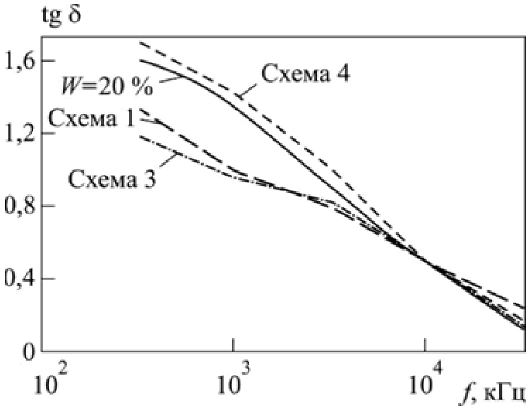


Fig. 2. Experimental dependence tgδ(f) by moisture 20 % in comparison of equivalent schemes 1, 3, 4

In fig. 2 shows the experimental frequency dependences of the tangent of the angle of dielectric losses of cotton. For scheme 1, the following expression is valid

$$\mathrm{tg}\delta=(\omega\tau)^{-1}, \qquad (3)$$

Where $\tau=RC$ – time constant. For equal weight functions, sum (1) has the form

$$\Delta=\sum^{n}(y_i - 1/\omega_i\tau)^2, \qquad (4)$$

where the role of the minimizing factor can be played by the time constant τ. The required value of τ is found from the equation

$$\partial\Delta/\partial\tau=0;$$

$$\tau=\sum_{i=1}^{n}\left(1/\omega_i^2\right)\Big/\sum_{i=1}^{n}(y_i/\omega_i).$$

(5)

(6)

For circuit 3, the dielectric loss tangent is defined as Let us introduce the following

$$a=(2\pi)^3 C_1 C_2^2 R_1 R_2 (R_1+R_2);$$

$$b=2\pi C_1 R_1;$$

$$c=(2\pi)^2 C_2\left[C_2(R_1+R_2)^2+C_1 R_1^2\right].$$

designations for the approximating coefficients:
Then expression (6) takes the form

$$\mathrm{tg}\,\delta=\left(af_i^3+bf_i\right)/\left(cf_i^2\right).$$

Here and below, the signal frequency f associated with cyclical frequency that ω ω= 2π. In this case, for equal weight functions, the sum (4) can be written as

$$\Delta=\sum_{i=1}^{n}\left(y_i-\frac{af_i^3+bf_i}{cf_i^2+1}\right)^2. \qquad (7)$$

After minimizing the error in the parameters a, b, c, according to condition (2), we

$$\left.\begin{array}{l}\sum\limits_{i=1}^{n}\left(y_i-\dfrac{af_i^3+bf_i}{cf_i^2+1}\right)\left(\dfrac{-f_i^3}{cf_i^2+1}\right)=0;\\ \sum\limits_{i=1}^{n}\left(y_i\quad\dfrac{af_i^3+bf_i}{cf_i^2+1}\right)\left(\dfrac{-f_i}{cf_i^2+1}\right)=0;\\ \\ \qquad\qquad\qquad\qquad\qquad=0.\end{array}\right\}\sum_{i=1}^{n}\left(y_i-\frac{af_i^3+bf_i}{cf_i^2+1}\right)\left(\frac{af_i^3+bf_i}{cf_i^2+1}\right)^2 f_i^2$$

obtain a system of equations

(8)

For Scheme 4, the following expression is valid

$$\frac{1+\omega^2 C_1 R_1 (R_1+R_2)}{}$$

(9)

$$\mathrm{tg}\delta=\quad \omega^3R_1^2R_2C_1^2C_2+\omega R_2(C_1+C_2)^{\cdot}$$

Let us introduce the following designations for the approximating coefficients:

$$\left.\begin{aligned}&\sum_{i=1}^{n}\frac{(cf_i^2+1)f_i}{(af_i^2+b)^2}=\sum_{i=1}^{n}y_i\frac{(cf_i^2+1)f_i^2}{af_i^2+b};\\&\sum_{i=1}^{n}\frac{cf_i^2+1}{(af_i^2+b)^2}=\sum_{i=1}^{n}y_i\frac{cf_i^2+1}{af_i^2+b};\\&\sum_{i=1}^{n}\frac{cf_i^2+1}{(af_i^2+b)^2}=\sum_{i=1}^{n}\frac{f_i}{af_i^2+b}.\end{aligned}\right\}\quad\left.\begin{aligned}&a=(2\pi)^3R_1R_2C_1^2C_2;\\&b=2\pi R_2(C_1+C_2);\\&c=(2\pi)^2 2C_1^2R_1(R_1+R_2).\end{aligned}\right\}$$

(10)

In this case, expression (9) takes the form

$$\mathrm{tg}\delta=cf_i^2/(af_i^3+bf_i).$$

(11)

Substitute expression (11) into relation (1) and obtain

$$\Delta=\sum_{i=1}^{n}\left(y_i\quad\frac{cf_i^2+1}{af_i^3+bf_i}\right).$$

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(12)

After minimizing the error in the parameters a, b, c according to conditions (2), we obtain the system of equations

Calculation Results and Discussion

The values of the coefficients a, b, c in equations (8), (13) were calculated by the steepest descent method. Using the graphoanalytical method, we obtained the frequency-humidity characteristic for equivalent circuits 1, 3, 4, built the frequency dependences of the dielectric loss tangent in the range of 105– 108 Hz and compared them with the experimental data. moisture content for cotton seeds $W = 20\%$(see fig. 2).

According to the results of a comparative analysis, it was found that the simplest parallel two-element RC-equivalent circuit (scheme 1) corresponds most closely to the real object of measurement in the entire investigated range of high frequencies of 105-108 Hz. Therefore, this scheme was chosen for further research.

Taking into account the obtained values of the coefficients and expressions (3) - (13), we calculated the values of the approximating functions tanδ tgδ,

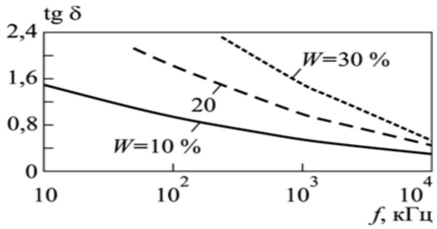

Fig. 3. Frequency dependence of the tangent of the angle of dielectric losses *tgδ* of cotton at different humidity *W*

Fig. 3. Dependence tgδ(*f*) by values of moisture 10, 20 and 30 %

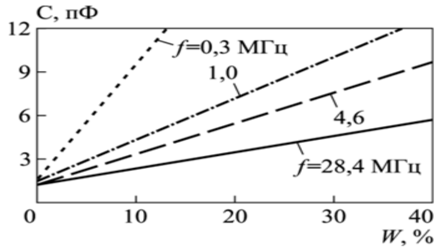

Fig. 4. Dependence of electrical capacity C on humidity W at different frequencies *f*

Fig. 4. Dependence of electric capacity, *C*, on moisture, *W*, by frequencies 28.4, 4.6, 1 and 0.3 MHz

the frequency dependences of which at the moisture content of cotton seeds $W = 10$ 20 and 30 % are shown in Fig. 3. For all humidity values, the tangent of the loss angle decreases monotonically practically according to the logarithmic law. As the moisture content of cotton seeds increases, the tgδ value increases, and the tgδ (W) curve becomes less monotonous.

In fig. 4 shows the dependence of the electric capacity on the moisture content of cotton seeds at frequencies of 28.4; 4.6; 1.0 and 0.3 MHz, plotted from the measured values of the active resistance and tension. Almost linear dependences of capacity on humidity are observed, and with a decrease in frequency, this dependence becomes less monotonic.

Conclusion

The mathematical model of a high-frequency moisture meter, based on the results of studies of the frequency dependence of the moisture content of cotton seeds, made it possible to represent the material under study (cotton seeds) in the form of a complex dielectric in an electric field.

The simplest parallel two-element RC-equivalent circuit selected according to the comparative analysis data most closely corresponds to the real object of measurement in the frequency range from 105-108 Hz. An almost linear dependence of the capacity of the measuring device on the moisture content of cotton seeds was revealed, and with a decrease in frequency, this dependence becomes less monotonous.These results will be useful in creating devices for measuring and controlling the moisture content of cotton seeds during technological processes.

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