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Hamdam Jabborov
Tashkent State Technical University, Tashkent city, Republic of Uzbekistan

Temurbek Rashidov
Tashkent State Technical University, Tashkent city, Republic of Uzbekistan, rashidovtemurbek6@gmail.com

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CAPACITIVE ELECTRODE BASED MOISTURE MEASUREMENT CONVERTER ERRORS AND HOW TO ELIMINATE THEM

X.SH.JABBOROV, T.E.RASHIDOV (Tashkent State Technical University, Tashkent city, Republic of Uzbekistan)*

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Abstract: *The article discusses the errors associated with the moisture measuring transducer that is based on the cylindrical electrode, along with their sources and calculation formulas for error elimination. The initial capacitance of the capacitive electrode humidity converter is dependent on its geometric parameters, such as the radii of the electrodes and their length. Accurate calculation of these geometric parameters enables the reduction of regular measurement errors in the input and switching circuit of the moisture converter to a minimum value, resulting in a significant increase in the informativeness and accuracy of the output signal. Consequently, some sources of measurement errors are eliminated or minimized during the design of the capacitive electrode moisture converter. To further reduce errors in the measurement chain and minimize the influence of internal and external destabilizing factors, there is a need to develop effective correction elements and schemes. Additionally, the article presents a method for calculating the total measurement error of the transducer by measuring the moisture content of scattered products with a capacitive electrode.*

Keywords: *Error, sources of error, entropic error, error calculation method, capacitive transducer, cylindrical electrode transducer, graph transitions*

Аннотация: *Мақолада цилиндрик электрод асосидаги намлик ўлчаш ўзгарткичининг хатоликлари, уларнинг келиб чиқиш манбалари ва хатоликларни бартараф қилиш учун ҳисоблаш формулалари келтирилган. Сиғим электродли намлик ўзгарткич дастлабки сиғим унинг геометрик параметрлари – электродларнинг радиуслари ва уларнинг узунлигига боғлиқдир. Айнан ана шу геометрик параметрларнинг аниқ ҳисобланиши намлик ўзгарткичининг кириш ва ўзгартириш занжиридаги мунтазам ўлчаш хатолигини минимал қийматигача камайиши имкониятини яратади, ўз навбатида чиқиш сигналини информативлиги ва аниқлигини бир неча баробар ошишига олиб келади. Демак, ўлчаш хатоликларининг баъзи манбалари сиғим электродли намлик ўзгарткичини лойиҳалаш давридаёқ бартараф қилинади ёки минимал қийматига эришилади. Ўлчаш занжиридаги хатоликларни янада камайтириш, ички ва ташқи дестабил факторларнинг таъсирини минимумга келтириш мақсадида эффектив ишлай оладиган коррекциялаш элементлари ва схемаларини ишлаб чиқиш зарурияти юзага келади. Шунингдек мақолада сиғим электродли сочилувчан маҳсулотларни намлигини ўлчаш ўзгарткичининг умумий ўлчаш хатолигини ҳисоблаш усули ҳам келтирилган.*

Калит сўзлар: *Хатолик, хатолик манбалари, энтропик хатолик, хатоликни ҳисоблаш усули, сиғимли ўзгарткич, цилиндрик электродли ўзгарткич, граф ўтишлари*

Аннотация: *В статье представлены погрешности преобразователя влажности на основе цилиндрического электрода, их источники и расчетные формулы для устранения погрешностей. Начальная емкость емкостного электродного преобразователя влажности зависит от его геометрических параметров - радиусов электродов и их длины. Точный расчет этих геометрических параметров позволяет снизить регулярную погрешность измерения во входной и коммутационной цепи преобразователя влажности до минимального значения, что в свою очередь приводит к увеличению в несколько раз информативности и точности выходного сигнала. Таким образом, при проектировании емкостного электродного преобразователя влаги устраняются некоторые источники погрешностей измерений или достигается их минимальное значение. Для дальнейшего снижения погрешностей в измерительной цепочке, минимизации влияния внутренних и внешних дестабилизирующих факторов необходима разработка эффективных элементов и схем коррекции. Также в статье представлена методика расчета суммарной погрешности измерения преобразователя измерения влажности рассыпанных продуктов емкостным электродом.*

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* Jabborov Hamdam Shaymardonovich – PhD, hamdam@list.ru, https://orcid.org/0000-0002-4239-3725;
Rashidov Timurbek Erkin ugli – Student, rashidovtemurbek6@gmail.com, https://orcid.org/0009-0004-2606-6312.

Ключевые слова*: ошибка, источники ошибок, энтропийная ошибка, метод расчета погрешности, емкостный преобразователь, преобразователь с цилиндрическим электродом, графовые переходы.*

Indroduction

When designing and constructing humidity measuring transducers based on capacitive electrode systems, it is crucial to research measurement errors, identify their sources, and uncover destabilizing factors, many of which arise during changes in the input size. Scientific works have extensively covered the analysis of errors in moisture meters with variable capacity [1-3,5]. This discussion focuses on the measurement errors specific to the cylindrical electrode transformer. By examining the construction of the transducer, its main elements, and analyzing the measurement results, a classification scheme for transducer measurement errors has been developed (see Fig. 1). The error sources of the moisture meter, based on cylindrical capacitive elements, are mainly categorized as methodical and instrumental errors. Additional errors arise from changes in internal and external factors affecting various parts of the measurement chain. Since any measurement process is inherently random, the sources of measurement error and their causes are also explained based on the theory of random processes.

Research methods and obtained results

The theory of random processes hinges on graph transitions that describe the state of the ongoing process. Constructing a graph model based on these transitions allows for the effective assessment of errors in the wet meter with a cylindrical electrode, which is based on a capacitive element, as well as the impact of internal and external destabilizing factors on these errors.

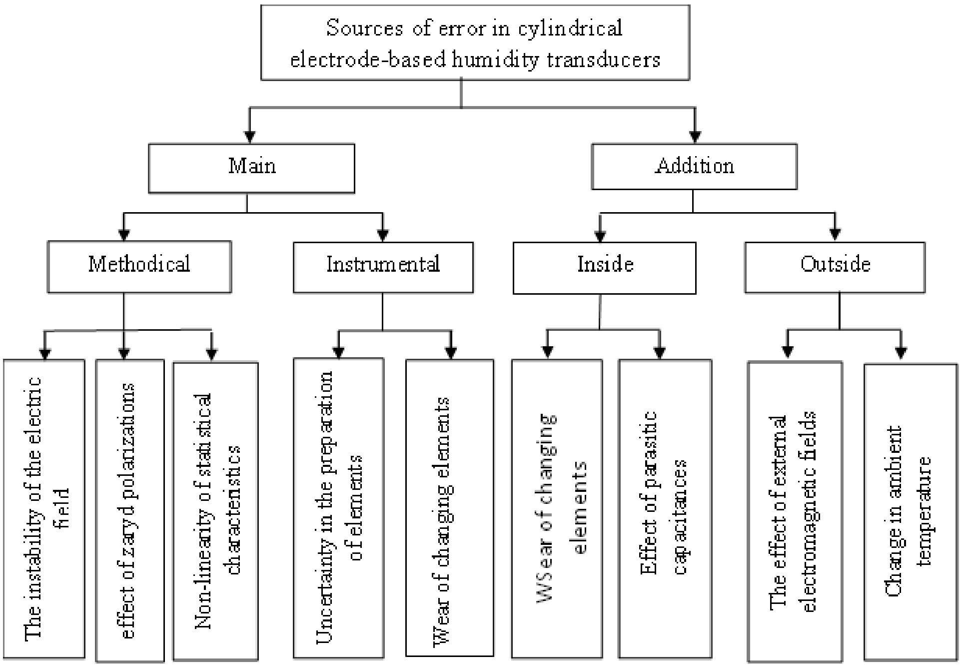

Fig.1. Classification scheme of sources of converter errors based on a cylindrical electrode

The entropic error distribution law is influenced by the structural elements of the moisture converter, which is based on capacitance electrodes, and by the variation of electric current in the input circuit. The mean square measurement error of the humidity transducer encompasses the errors associated with certain elements of the transducer.

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + ... + \sigma_n^2},$$

in this σ_1, σ_2, σ_n – errors of the converter elements.

Fig. 2 illustrates the structural diagram of the graph transitions of the humidity transducer measurement errors, which are based on the capacitive electrode. When a substance requiring humidity measurement is positioned between the electrodes of the capacitive electrode humidity sensor, the electric field intensity between the electrodes undergoes a physical change. This change in the field is considered analogous to an alteration in electric current in graph transitions, resulting in a shift in the transducer's capacity, which is contingent on the dielectric strength of the substance.

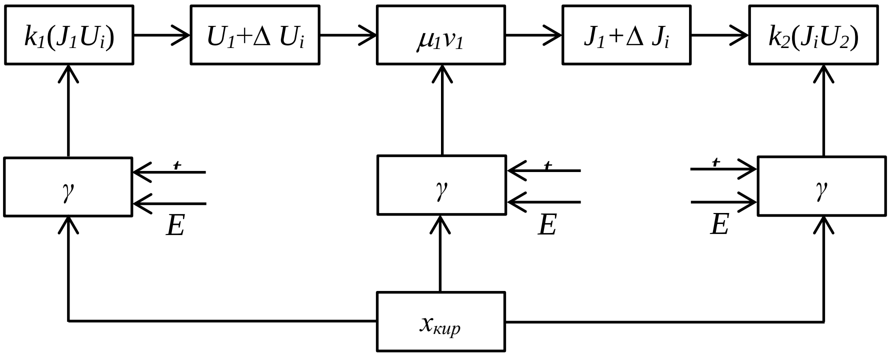

Figure 2. The structural scheme of the graph transitions of the measurement errors of the moisture converter based on capacitive electrodes

By determining the mathematical expression for the electric current intensity, it becomes feasible to link it to the aforementioned quantities and identify the specific stages of the measurement process where errors occur.

The distribution of the electric field current strength across the height of the transducer with a capacitive electrode along its length is derived from the following expression:

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$$E_C = \frac{U_2}{h}, \tag{1}$$

in this U_2 – output voltage; h – the length of the switch.

$$U_2 = U_1 \frac{4\pi\varepsilon_0 \cdot h}{R \cdot \ln\left[\dfrac{h+\sqrt{h^2+r^2}}{r}\right]}\left(e^{\frac{W\ln\varepsilon}{1+W}} - 1\right)$$

Substituting the value of the output voltage from the given formula into equation (1) yields the following mathematical expression, which represents the distribution of the electric field strength current across the height of the converter:

$$E_C = U_1 \frac{4\pi\varepsilon_0}{R \cdot \ln\left[\dfrac{h+\sqrt{h^2+r^2}}{r}\right]}\left(e^{\frac{\omega\ln\varepsilon}{1+\omega}} - 1\right), \tag{2}$$

The derived equation highlights that the measurement errors in the input variable circuit are contingent on the key characteristics of the electric field current, such as its homogeneity and equipotentiality.

When a wet material is introduced into a homogeneous and equipotential field, the potential difference remains consistent across all points, ensuring a stable change in the dielectric strength of the material and the capacity of the transducer. This results in a significant reduction in measurement error. Conversely, the non-homogeneity of the transducer's electric field current and a decrease in its equipotentiality will cause variations in potential differences at different points of the wet substance.

The initial capacitance of the capacitive electrode humidity converter is determined by its geometric parameters, including the radii of the electrodes and their length. Accurate calculation of these geometrical parameters enables the reduction of regular measurement errors in the input and switching circuit of the moisture converter to a minimum, resulting in a significant increase in the informativeness and accuracy of the output signal. Consequently, certain sources of the aforementioned measurement errors are eliminated, or their minimum value is achieved during the design of the capacitive electrode moisture converter. To further minimize errors in the measurement chain and reduce the influence of internal and external destabilizing factors, it is essential to develop effective correction elements and schemes.

Components of measurement errors based on graph transitions of a capacitive electrode moisture converter (U_1, I_1), change size (I_1, U_i, I_i), element sensitive to changes in electric field current [U_i,(I_i),U_1], size measurement (U_2, I_2) and influence of input size ($x_{кир}$, κ[I_1,U_i,(I_i), $x_{кир}$]) occurs in chains.

Variations in the current and voltage supplied to the circuit of the capacitive electrode humidity measuring transducer result in fluctuations in the frequency of the measuring generator, leading to measurement errors in the transducer's input circuit. The alteration of the inter-chain function, which characterizes the graph transitions, is associated with the instability of temperature, pressure, and humidity in the external environment, as well as changes in the material properties of the capacitive electrode humidity transducer. These factors contribute to measurement errors.

As previously mentioned, the quality of the change in the input magnitude, i.e., how much of it is converted into a useful signal, is closely linked to the conversion of the energy of the electric field current into an active signal. A decrease in the active signal in this part of the measurement process indicates the destabilizing effect of temperature and physical (electromagnetic) fields on the energy of the electric field. Measurement errors occur in the measuring circuit of the capacitance converter and the input magnitude sensing circuit [$I_i(U_i)$, $U_2(I_i)$] due to the measurement scheme type, the material of the capacitive electrodes, and their wear over time. Additionally, constituent elements in the measurement scheme create various measurement errors as a result of changes in characteristics and deviations from the limits of permissible errors.

The fundamental nature of the mathematical model based on graph transitions lies in its ability to identify the source of the physical field, the channel of the physical field distribution, and the measurement errors that occur at all stages of the input magnitude change, especially when analyzing it from the perspective of electric field current distribution. In this scenario, the input size can directly impact the conversion stages mentioned above. If stable conditions are not maintained in the input circuit, including ambient temperature, pressure, humidity, and voltage stability in the constant current circuit, changes in the electric field current in the aforementioned input magnitude change circuits will occur, leading to measurement errors and resulting in an overshoot of the errors of the inter-chain transfer function. Hence, the identification of the primary error sources in the moisture measurement converter for grain and grain products with a capacitive electrode, as well as the development of effective solutions, is accomplished through the use of a mathematical model based on phase transitions.

The determination of measurement errors is a crucial metrological characteristic of the capacitive electrode humidity transducer, as it directly impacts the measurement error of the moisture meter device based on this transducer. To ascertain the total error of the grain and grain products moisture measurement transducer, it is essential to consider the measurement errors generated in the size change chain, measuring elements, and its system, all of which are associated with its structural elements. Furthermore, the use of advanced methods of mathematical statistics in the processing of measurement results is important for reducing the overall measurement error of the capacitive electrode transducer. For instance, employing correlation analysis methods can reduce the measurement error of the capacitive moisture meter by 5-7% when building the calibration characteristic of the moisture meter.

When analyzing the measurement error of a capacitance electrode humidity transducer, the mean square deviation of the error is typically obtained from the regression equation's straight line, i.e.

$$\beta = \sqrt{D(\beta)(1-\rho^2)}, \qquad (3)$$

where ρ – relative correlation; $\kappa = 1-\rho^2$ – coefficient of indeterminacy.

The regression equation, derived from processing the measurement results, is an approximation that represents the relationship between the output value of the moisture meter and the material's moisture content.

The primary indicator of this approximation is the correlation coefficient, also known as the relative correlation. A larger correlation coefficient indicates a stronger correlation between two random variables.

If the relative correlation equals one, it indicates a genuine functional relationship between the two associated quantities. Consequently, the mean square deviation from the regression equation line cannot accurately represent the true value of the material moisture measurement error.

To assess the overall error of the device used to measure the moisture content of grain and grain products with a capacitive electrode, we view the moisture meter as comprising two transducers connected in series (see Figure 3).

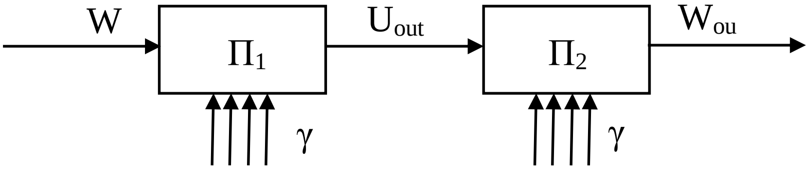

Figure 3. Change of input size under the influence of unstable factors:
in this γ – unstable factors; U_{out} – output signal of the converter; W – measure not humidity value; W_{out} – measured value of humidity; $П_1$ ва $П_2$ – moisture exchangers.

The transducer П_1 measures the size σ, which in turn changes to the output signal П_2 representing the moisture at the outlet of the converter, W_{out}. The root mean square error of moisture measurement is determined from the mathematical expression, considering two independent random errors, based on the structure diagram in Fig. 4.3.

$$\sigma = \sqrt{\sigma^2_{\text{П}_1} + \sigma^2_{\text{П}_2}}, \qquad (4)$$

where $\sigma^2_{\text{П}_1}$ ва $\sigma^2_{\text{П}_2}$ – the square errors of the variables $П_1$ and $П_2$, respectively.

The measurement error of the primary converter, П_1, can be determined experimentally, while the error of the converter switch, П_2, is limited by a transfer function, making detection possibilities restricted. To address these challenges, we employ elements of informational measurement theory to determine the total error of the wet meter. Viewing the converter as an existing information transmission channel, we consider a signal with entropy M(u) at its input and the resulting noise fluctuations H(Δ) having an entropy. According to Shannon's theorem from the theory of measurements, the errors created by unstable factors and other random processes are equal to their entropy. From this perspective, the information at the output of the transmission channel consisting of a converter is as follows, i.e.

$$q_{\Pi_2} = q_{\Pi_1} - \mathrm{H}(\Delta), \tag{5}$$

where q_{Π_1} – the amount of information at the input of the transmission channel.

When the output signal of converter $П_1$ shifts from u_1 to u_2, the output signal of converter $П_2$ shifts from w_1 to w_2. We denote the output signal detection errors of converters by Δu and Δw, respectively.

In the theory of information measurement, the determination of the quantity *u(w)* is defined by the probability distribution of the density of measurement errors before the measurement, when the signal changes from u_1 to u_2 (from w_1 to w_2).

$$P(u) = \frac{1}{u_1 - u_2} \text{ ёки } \quad P(w) = \frac{1}{w_1 - w_2}; \tag{6}$$

After measurement, the magnitude of $2\Delta u$ ($2\Delta w$) is determined by the expressions, and the probability of measurement errors is calculated as follows:

$$P(u) = \frac{1}{2\Delta u} \text{ ёки } P(w) = \frac{1}{2\Delta w}. \tag{7}$$

The values derived individually from (7) indicate that the signal of converter $П_1$ ($П_2$) is in the state $u_i(w_i)$ and is determined by the following expressions:

$$q_{\Pi_2} = -\lg \frac{2\Delta u}{u_1 - u_2}, \qquad q_{\Pi_2} = -\lg \frac{2\Delta w}{w_1 - w_2}. \tag{8}$$

We will now initiate the process of determining the entropy of noise fluctuations in the information signal transmission channel. Once the material's moisture and grading characteristics stabilize based on the output signal of the capacitive electrode moisture meter, a functional connection is established between the output signal of the $П_1$ converter and the measured value. Drawing from the theory of correlation analysis, it becomes feasible to ascertain the correlated random variable, which is contingent on the quadratic factor of the relative correlation. Subsequently, the coefficient of determination $П_1$ determines the likelihood of linking the material's moisture content with the transducer's output signal. Thus, this connection signifies the calibration characteristic of the moisture transducer with a capacitive electrode. The formula for determining the entropy of noise fluctuations in the information transmission channel of the transducer is as follows:

$$\mathrm{H}(\Delta) = -\lg \rho^2; \tag{9}$$

Putting mathematical expressions (8) and (9) into expression (5), we get:

$$\lg \frac{2\Delta w}{w_1 - w_2} = \lg \frac{2\Delta u}{u_1 - u_2} - \lg \rho^2. \tag{10}$$

where

$$\frac{\Delta w}{w_1 - w_2} = \frac{\Delta u}{(u_1 - u_2)\rho^2}, \tag{11}$$

$$\delta w = \frac{\Delta u}{(u_1 - u_2)\rho^2}. \tag{12}$$

Mathematical expressions (11) and (12) correlate the absolute and relative measurement errors of the capacitance electrode wet meter.

Thus, knowing the absolute or relative measurement error of the transducer $П_1$ and the correlation coefficient of the calibration characteristic, it is possible to determine the absolute or relative error of humidity measurement.

The research outlined above demonstrates that the entropic value of the measurement error of the capacitive electrode moisture transducer reflects the magnitude of the error. In the context of informational measurement theory, measurement accuracy is solely determined by the entropic error value, which can be calculated using the following formula:

$$\Delta_Э = k_Э \cdot \sigma, \tag{13}$$

where $k_Э$ is the entropic coefficient, measurement errors depend on the type of distribution law; σ is the value of the average squared error of the measurements, determined by the dispersion of the measurements, therefore, with the decrease of the dispersion, the average squared error also decreases. The entropic coefficient is calculated during the analysis of the measurement results obtained from experiments and the calibration of the wet meter.

Therefore, utilizing the equations mentioned above, we derive the following formula for computing the measurement error of the capacitance electrode moisture meter:

$$\delta w = k_Э \frac{\sigma}{(u_1 - u_2)^2 \rho^2}. \tag{14}$$

Experimental studies indicate that a range of 50 to 100 measurements is necessary to establish the distribution pattern of measurement errors accurately when calculating the entropy coefficient. For instance, this coefficient must be computed for various wet meters. A quantity of 15 to 30 measurements is satisfactory to determine the mean squared error of the measurements and the squared error of the deviation of the regression equation line from the true value, a range of 15 to 30 measurements is sufficient.

Conclusion

The method developed for assessing and analyzing the overall measurement error of the capacitance electrode wet meter fully satisfies the requirements of informational measurement techniques. It also has the potential to be applied in determining the measurement error of other measuring devices. This method offers a high likelihood of moisture binding, indicating that the scaling characteristic closely approximates its true value. Consequently, entropy serves as a measure of the correlation between the output signal of a capacitive electrode moisture meter and the moisture content of the material being studied.

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AN EXPERIMENTAL INVESTIGATION OF THE NEW VIBRATION VISCOMETER

J.U.SHAMURATOV (Tashkent State Technical University, Tashkent city, Republic of Uzbekistan)*

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Abstract: *The characteristics of the new oscillating-plate viscometer have been investigated experimentally. The results obtained are as follows: the resonant frequency of plate oscillation decreases with increasing viscosity; the apparatus constant* K *determined experimentally includes the end and slip effects; the dimensions of the plate should be determined by referring to empirical relations between* $\rho\mu$ and $\Lambda\left(\equiv\left\{\left(\frac{E_a}{E}\right)-1\right\}^n\right)$ *for various dimensions of the plate; where* ρ *is the density,* μ *is the viscosity;* E_a *the resonant amplitude of plate in the air;* E *the amplitude of plate in a liquid, and* n *a constant.*

If the distance between the plate and the wall of the vessel is longer than about one wavelength of the wave produced by the plate, the effect of the reflected wave from the wall can be neglected.

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* Jamshidbek U. Shamuratov – PhD student, jamshid.shamuratov.phd2022@gmail.com, https://orcid.org/0000-0002-6907-066X.