

Primary measuring transducer of moisture content for grain quality control

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Abstract

The main task of the research is the development of the primary capacitive measuring transducer that can perform testing influences on the material under research, applied for automatic "type uncertainty" method error compensation, that takes place because of the method of measurement imperfection. To estimate the relevant level of testing influences a group of different materials with 2, 2.5, 3 and 3.5 dielectric permittivity values was taken for 0, 10, 20, 30 and 40% of moisture content control points. The primary measuring transducer of moisture content is organized with an electrode system in a form of V-type plates, which is fixed on the internal surface of two dielectric rings. Testing influences on the substance are reproduced directly in the capacitive primary transducer by simple metallic plates with fixed thickness introduction into the space between separate electrodes of an electrode system. A prototype product of the primary measuring transducer had been experimentally tested together with the new method of moisture measurement, which includes two additive, two multiplicative and two complementary testing influences on the material under research. Moisture content with nominal values 0, 10, 20 and 30% was reproduced by certain group of grains with different dielectric permittivity values. Experimental setup of an adaptive moisture meter was assembled using the substitution method of measurement to provide good accuracy for the conditions of capacitance measurement in substances with significant dielectric losses. The accuracy of moisture measurement was defined as discrepancy between average measured and nominal moisture content and as an uncertainty of this discrepancy in a form of type A uncertainty.

Keywords: moisture measurement; grain; primary measuring transducer; type uncertainty method error; testing influence; accuracy estimation.

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Introduction

Grain growing in Ukraine is a strategic and most effective branch of economy. In the Law of Ukraine "About Grain and Grain Market in Ukraine", a lot of attention is paid to grain state quality control and its storage conditions. Modern performance indexes of grain are regulated with a group of national standards, where it is mentioned that grain moisture content shouldn't be more than 14.5...15.5%. Ukraine produces 2.5 million tons of grain per year and 1.5 million tons from that quantity needs quality improvement. One of the most popular ways of quality improvement is one or two times moistening with further conditioning to the 12...13% moisture level, that allows to improve bakery properties noticeably.

Moisture measurement with high accuracy is really necessary for all these examples. Big number of factors influence on the accuracy of moisture measurement. Among them we can emphasize physicochemical com-

position, granulometric composition and temperature variation. Not only material's type or sort has an effect on its physicochemical composition, but conditions of extraction, processing, etc., that is the list of factors, complicated for analytic forecasting. Granulometric composition of different bulk materials is far from ideal what decreases the repeatability of measurements. Temperature influence, in its turn, can be taken into account by the introduction of correction coefficients into the result of moisture measurement.

Problem statement

Moisture control is typical for the significant number of operations in extracting, processing and production of different materials. Now we have approximately 33% of moisture meters represented by dielcometer instruments with capacitive primary transducers. Moisture meters of this type have complementary error of measurements (type uncertainty), connected with dif-

ferent values of dielectric permittivity for the materials under research in dehydrated state. The influence of this error is usually significant and traditional ways of its compensation can be effective when we know the composition of the material under research.

In other cases the effectiveness of traditional compensation methods essentially decreases.

Mainly because of that further improvement of the existing methods of moisture measurement with a task to solve the problem of type uncertainty compensation is a relevant and perspective mission.

Analysis of recent researches and publications

In moisture meters, present on the modern market, different physicochemical composition in the most cases can be taken into account in the way of metering curves or rating coefficients introduction into the microprocessor block memory for maximal number of the materials under research with a possibility of separate calibration before each measurement [1–3]. But it is impossible to get analytic forecast of chemical composition and different features of all the materials under research. That is why mentioned above methods of type uncertainty compensation have local effectiveness and are not versatile.

Besides, the analysis of measurement methods based on dielcometer principle was carried out [4]. Separate group of methods was detected, where special testing influences should be fulfilled to define the initial moisture value of the sample under research. Testing influences can be implemented in the form of measured out water volumes addition with further mixing, introduction of measured volume of a material with certain dielectric permittivity or capsules with water of a certain form.

Direct addition of water does into the material with further mixing can be hardly possible for some cases, for example, when we have measurements in a flow or when the material with high moisture content is under research. Besides that, for a big number of technological processes (grain softening, production of oil-water or coal-water slurries) it is necessary to maintain a certain value of moisture and measured out water volumes addition can't be accepted. Application

of leak-proof capsules with water is ineffective from the production manufacturability point of view.

Main purpose of the research is to create a primary transducer of moisture content with a design, which could provide the most simple and manufacturable way to fulfill testing influences on the material under research with a task to compensate material's type influence on the result of measurement.

Primary measuring transducer of moisture content

Before we discuss testing influences on the material, it's necessary to estimate their relevant level. For that purpose a group of different materials with dielectric permittivity values ϵ_n , equal to 2, 2.5, 3 and 3.5 was taken. Then five control points of moisture content W were chosen for these materials with values 0, 10, 20, 30 and 40% of moisture.

Average change of dielectric permittivity values for the binary material-water systems with mentioned above moisture content ($W=0$, $W=10$, $W=20$, $W=30$, $W=40\%$) was estimated using universal equations of Wiener, Botcher and Kubo-Nakamura [5–9]. Results are summarized in Table 1.

Main purpose of such a check-up was to determine the percentage of binary mixture dielectric permittivity change for the certain volumes of water added to different materials.

Primary measuring transducer is organized with an electrode system 1 (Fig. 1) in a form of V-type plates. System of electrodes is fixed on the internal surface of two dielectric rings 2 and 3. To make the implementation of testing influences convenient, construction of the transducer has two internal dielectric rings 4 and 5.

Testing influences on the substance are reproduced directly in the capacitive primary transducer by simple metallic plates 6, 7 with fixed thickness introduction into the space between separate electrodes of an electrode system 1. To preform two additive testing influences on the material under research primary transducer can be conventionally divided into three measuring sections. In accordance with Table 1, to simulate 10% water addition to the substance it is necessary to increase dielectric permittivity or primary

Table 1

Results of dielectric permittivity calculations

Average change of dielectric permittivity ϵ , %	Moisture content W (absolute values)				
	0	0.1	0.2	0.3	0.4
Equation of Wiener	0	29.8	66.2	111.61	169.79
Equation of Botcher	0	27.11	54.23	81.33	108.44
Equation of Kubo-Nakamura	0	26	58.8	98.42	144.86
Average change in total, %	0	27.64	59.74	97.12	141.03

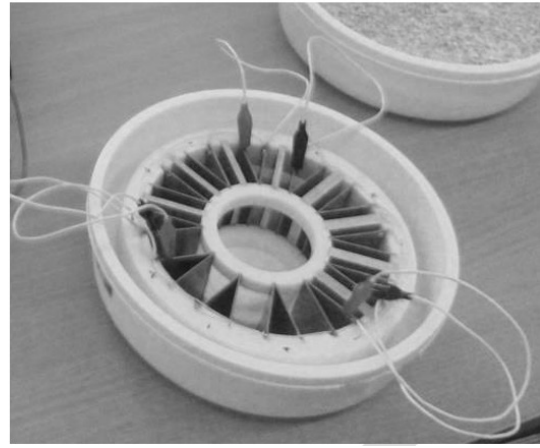
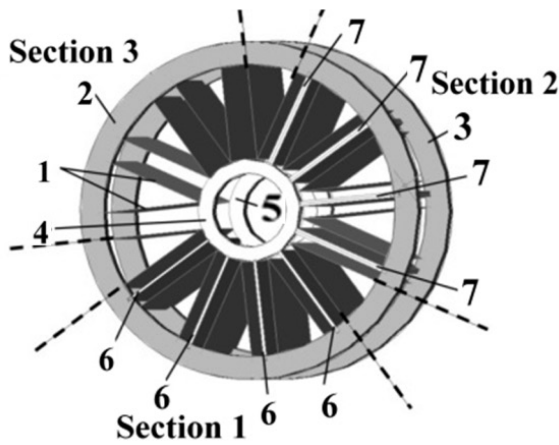


Fig. 1. Primary measuring transducer: external look and a prototype product

transducer's capacitance by 27.64% or in 1.2764 times. To provide second testing influence on the substance under research capacitance C of four capacitors from section 2 must be increased by 59.74% or in 1.5974 times. Gap between the electrodes, designated as Z , should be decreased by the same value.

Primary transducer's prototype product has such geometrical dimensions (Fig. 1): electrodes' length (distance between rings 2 and 3) is equal to $l = 50$ mm; gap between electrodes $Z = 20$ mm; internal diameter of dielectric rings $D = 150$ mm; electrodes' width (distance between rings 2 and 4) $L = 0.5\sqrt{(D^2 - Z^2) - 1.866Z} = 37$ mm.

In correspondence with [10], capacitance C of a flat capacitor with metallic plate between the electrodes will depend only from metallic plate thickness and can be calculated using the formula:

$$C = \frac{\varepsilon\varepsilon_0 S}{2d}, \quad (1)$$

where d is a distance from the edge of an electrode to the edge of metallic plate. Knowing that, it is possible to calculate thickness d_1 of one metallic plate 6 using formula (2) and thickness d_2 of one metallic plate 7 using formula (3):

$$d_1 = Z - \frac{Z}{1.2764} = 0.2165 \cdot Z = 4.33 \text{ mm}, \quad (2)$$

$$d_2 = Z - \frac{Z}{1.5974} = 0.374 \cdot Z = 7.48 \text{ mm}. \quad (3)$$

Calculation of primary measuring transducer's electric capacitance

At first electric capacitances of sections 1, 2 and 3 for empty primary measuring transducer were

$$W = \left| \frac{(C_3'' - C_3) \Delta W'}{(C_4'' - C_2) - (C_3'' - C_3)} - \frac{(C_3' - C_3) \Delta W}{(C_4' - C_1) - (C_3' - C_3)} + 0.033 \right| \cdot 833 + \left| \frac{\Delta W' (C_3'' - C_3)}{(k' - 1)(C_2 - C_3)} - \frac{\Delta W (C_3' - C_3)}{(k - 1)(C_1 - C_3)} - 0.033 \right| \cdot 800. \quad (5)$$

calculated. Section 1 contains four connected in parallel capacitors, where gap between electrodes is equal to $Z_1 = Z - d_1$. Section 2 has four capacitors with a gap $Z_2 = Z - d_2$. Section 3 is free from metallic plates and has four capacitors with a gap Z between electrodes. General electric capacitance for the capacitors of section 1 can be calculated using the formula:

$$C_1 = \varepsilon_0 \varepsilon \left[g_{01} + 2 \left(g_{21} + g_{41} + g_{61} + g_{81} + 2g_{101} + 2g_{121} \right) \right] \cdot 4, \quad (4)$$

where g_{01} – spatial characteristics of basic electric field, m; g_{21} – spatial characteristics of external field in a form of half cylinder for the side l ; g_{41} – the same in a form of half cylinder for the side L ; g_{61} – the same in a form of half tube for the side l ; g_{81} – the same in a form of half tube for the side L ; g_{101} – the same in a form of spheric quadrants; g_{121} – the same in a form of quadrants of the spheric shells.

Method of spatial characteristics calculation can be found in Table 2.

Capacitance value C_1 would be equal to:

$$C_1 = \varepsilon_0 \varepsilon \left[g_{01} + 2(g_{21} + g_{41}) \right] \cdot 4 = 8.85 \cdot 10^{-12} \times \times 1 \left[0.1181 + 2(0.013 + 0.0096) \right] \cdot 4 = 6.28 \text{ pF}.$$

Spatial characteristics calculations for C_2 and C_3 capacitances of the primary measuring transducer sections 2 and 3 are given in Table 3. Described primary measuring transducer was developed as a part of moisture measurement method in bulk and liquid dielectric substances [11, 12], where moisture content can be calculated using formula (5):

Calculations of C_1 capacitance spatial characteristics

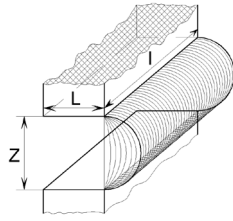
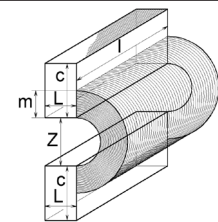
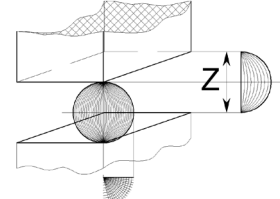
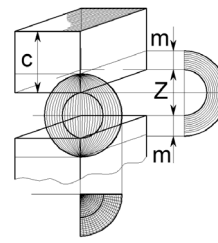
Spatial characteristic	Formula	Image of a spatial characteristic	Result, m
g_{01}	$\frac{L \cdot l}{Z - d_1}$		0.1181
g_{21}	$0.26 \cdot l$		0.0130
g_{41}	$0.26 \cdot L$		0.0096
g_{61}	$\frac{l}{\pi} \ln \left(\frac{2m}{Z - d_1} + 1 \right)$		0.0019 ($\rightarrow 0$)
g_{81}	$\frac{L}{\pi} \ln \left(\frac{2m}{Z - d_1} + 1 \right)$		0.0014 ($\rightarrow 0$)
g_{101}	$0.77 \cdot (Z - d_1)$		0.0012 ($\rightarrow 0$)
g_{121}	$\frac{m}{4}$		0.00025 ($\rightarrow 0$)

Table 3

Calculations of C_2 and C_3 capacitance spatial characteristics

Spatial characteristic	Formula	Result, m	Spatial characteristic	Formula	Result, m
C_2 capacitance			C_3 capacitance		
g_{01}	$\frac{L \cdot l}{Z - d_2}$	0.1478	g_{01}	$\frac{L \cdot l}{Z}$	0.0925
g_{21}	$0.26 \cdot l$	0.0130	g_{21}	$0.26 \cdot l$	0.0130
g_{41}	$0.26 \cdot L$	0.0096	g_{41}	$0.26 \cdot L$	0.0096
$C_2 = \epsilon_0 \epsilon [g_{01} + 2(g_{21} + g_{41})] \cdot 4 = 7.99 \text{ pF}$			$C_3 = \epsilon_0 \epsilon [g_{01} + 2(g_{21} + g_{41})] \cdot 4 = 4.87 \text{ pF}$		

Table 4

Values of electric capacitances in picofarads for dehydrated and moist bulk material

W	C_1	C_2	C_3	C_3'	C_4'	C_3''	C_4''
$W = 0\%$	21.98	27.97	17.05	34.10	43.96	68.20	111.86
$W = 20\%$	36.05	45.87	27.96	55.92	72.11	111.84	183.48

Main idea of the method is that we take a sample of material under research and get a first reading from the capacitance primary transducer C_3 (it will be the capacitance of section 3). Then we get a second reading from the initial transducer C_1 as a capacitance of section 1 with first group of metallic plates (they simulate adding 10% of water into the sample as a first additive test). To create the first multiplicative test and get a third reading from the initial transducer value of capacitance C_3 was increased two times (C_3' in the formula). First complementary test (reading number four) was received by two times increasing the capacitance C_1 (C_4' in the formula). Next, fifth reading from the capacitance primary transducer can be taken from section 2 as a capacitance C_2 (second additive test). Reading number six must be performed as a second multiplicative test $4 \cdot C_3 = C_3''$, and the last reading is a second complementary test $4 \cdot C_2 = C_4''$.

Values of all capacitances were calculated for the conditions where moisture content $W = 0\%$ and $W = 20\%$, and dielectric permittivity of a bulk material is equal to $\epsilon_n = 3.5$ (Table 4).

Obtained values were substituted into (5) with a result $W = 0.77\%$ for dehydrated substance and $W = 20.157\%$ for moist substance. We can see that method error is acceptable and formula (5) is workable.

Experimental researches

To fulfill experimental researches moisture content with nominal values 0, 10, 20 and 30% had to be reproduced for such substances as: pearl barley ($\epsilon = 3.68$); poppy ($\epsilon = 3.56$); millet ($\epsilon = 3.17$); pea ($\epsilon = 2.97$); wheat cereals ($\epsilon = 2.55$) [12]. Mass of each sample was approximately 600 g, and for their preliminary dehydration 30 standard aluminum weighing bottles with 20 g weights of grain were used. Empty weighing bottles were weighed with ± 0.01 g accuracy [13] using electronic scales "LEV 600-0.01". In accordance with [14], weighing bottles with opened leads should be placed in a drying oven to dry in 130 °C temperature during 120 minutes. Air sterilizer "GP-10" with required metrological characteristics was used for that purpose.

Fig. 2 shows the experimental setup. It has a container with primary measuring transducer, secondary measuring transducer, oscilloscope Tektronix 2213A to control the shape and duration of pulses, taken from secondary measuring transducer's check point,

variable air capacitor, digital multimeter UTM 18803 to measure dc voltage on the output of a secondary transducer and accurate RLC-meter UTM 1612 to measure capacitance value of the variable air capacitor [15].

Container with primary measuring transducer was filled with substance under research. Then capacitive sensors of three sections were connected one by one to the input of secondary measuring transducer and three values of dc voltage from its output were fixed. After that primary measuring transducer was substituted by variable air capacitor. Using method of substitution electric capacitances of each primary measuring transducer's section were defined.

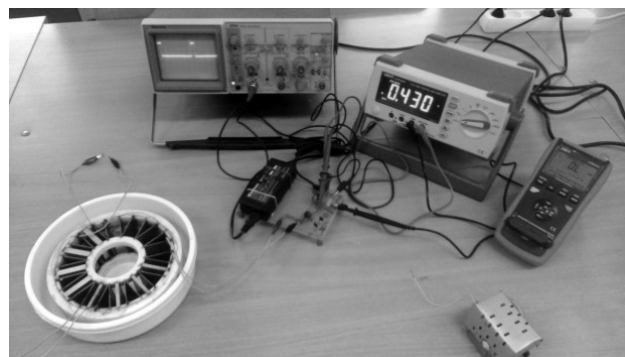


Fig. 2. Experimental setup for moisture measurement

Results and discussion

Averages of 10 measurements for primary transducer's electric capacitances C_1 , C_2 and C_3 , filled with materials under research in dehydrated state and with moisture content of $W = 10\%$, $W = 20\%$ and $W = 30\%$ are shown in Table 5.

Rest of the capacitances, mentioned in Tables 4, 5, were calculated in accordance with the principle described right after formula (5).

Now it became possible to check the testing algorithm (5) interaction with the results of capacitance measurement (averages) shown in Table 5. Results of moisture calculation for mentioned materials under research can be found in Table 6.

It is possible to estimate the method part of moisture measurement absolute uncertainty by using: discrepancy $\bar{\Delta}_m$ of measured moisture content average W_{mi} and standard moisture value W_{si} , and uncertainty of that discrepancy in a form of type A uncertainty.

$$\bar{\Delta}_m = \frac{1}{20} \sum |W_{mi} - W_{si}| = \frac{|0.503-0|}{20} + \frac{|0.445-0|}{20} + \frac{|0.622-0|}{20} + \frac{|0.701-0|}{20} + \frac{|0.001-0|}{20} + \frac{|10.882-10|}{20} + \frac{|10.204-10|}{20} + \frac{|9.758-10|}{20} + \frac{|10.843-10|}{20} + \dots + \frac{|28.692-30|}{20} = 0.586\%$$

$$U_{Aw} = \sqrt{\frac{\sum (W_{mi} - W_{si})^2}{20}} = 0.673\%$$

Table 5

C_1 , C_2 and C_3 capacitance average values

\bar{C}_i , pF	W , %							
	0	10	20	30	0	10	20	30
	Pearl barley				Poppy			
\bar{C}_3	57.02	73.53	93.19	117.73	54.10	69.46	88.29	111.50
\bar{C}_1	73.40	87.07	110.39	138.61	69.27	82.26	104.40	131.62
\bar{C}_2	93.49	102.80	130.69	164.42	88.01	97.25	123.47	155.70
	Millet				Pea			
\bar{C}_3	48.16	62.25	79.45	100.71	45.12	58.75	74.91	95.18
\bar{C}_1	62.14	73.76	93.69	118.82	58.69	69.46	88.73	112.28
\bar{C}_2	79.21	87.08	111.20	140.61	74.63	82.09	104.86	133.06
	Wheat cereals							
\bar{C}_3	38.82		50.51		64.75		82.51	
\bar{C}_1	50.24		59.93		76.50		97.56	
\bar{C}_2	64.46		70.79		90.31		115.42	

Table 6

Moisture content of the materials under research

Substance	Moisture content W , %			
	0	10	20	30
Pearl barley	0.503	10.882	20.487	29.818
Poppy	0.445	10.204	19.066	30.963
Millet	0.622	9.758	19.914	30.705
Pea	0.701	10.843	20.678	30.94
Wheat cereals	0.001	10.396	19.405	28.692

Conclusions

In the described model of primary measuring transducer we have metallic plates introduced into the gap between electrodes instead of capsules with water or direct water addition. It was divided into three sections.

First section is free from testing influences on the material under research, in second section 10% of water addition is simulated by increasing its capacitance into 27.64%. Third section simulates 20% addition of water and, to provide it, electrical capacitance of this section should be increased in 59.74%.

Thickness of metallic plates and electrical capacitances of three empty (without a material) sections were calculated. In the process of experimental researches a group of bulk materials with different dielectric permittivity values was used: pearl barley ($\epsilon=3.68$); poppy ($\epsilon=3.56$); millet ($\epsilon=3.17$); pea ($\epsilon=2.97$); wheat cereals ($\epsilon=2.55$). To get samples with needed amount of water, preliminary drying to the state of maximal water deletion was applied in accordance with [10, 11].

Experimental setup was assembled using the substitution method of measurement. As a result, the accuracy of moisture measurement was defined as a discrepancy Δ_m of measured moisture content average W_{mi} and standard moisture value W_{si} , and uncertainty of that discrepancy in a form of type A uncertainty. It helped to confirm that received accuracy values correspond with requirements to grain moisture meters set out in [16].

Первинний вимірювальний перетворювач вмісту вологи для контролю якості зерна

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Анотація

Коли мова йде про вимірювання вмісту вологи зерна з використанням ємнісних вологомірів, необхідно брати до уваги різні значення діелектричної проникності для різних типів зерна у зневодненому стані, що спричиняє появу методичної похибки, яку можна назвати "сортовою невизначеністю". Основною метою дослідження є зменшення значення сортової невизначеності шляхом розроблення ємнісного вимірювального перетворювача, здатного здійснювати тестові впливи на досліджувану речовину, реалізовані для автоматичної компенсації "сортової невизначеності", спричиненої недосконалістю методу вимірювання. Щоб оцінити актуальні рівні тестових впливів, було обрано речовини зі значеннями діелектричної проникності 2, 2.5, 3 та 3.5 для контрольних точок вмісту вологи 0, 10, 20, 30 та 40%. Первинний вимірювальний перетворювач вмісту вологи утворено системою електродів у формі V-подібних пластин, зафіксованих на внутрішній поверхні двох діелектричних кілець. Тестові впливи на речовину відтворюються безпосередньо у ємнісному первинному перетворювачі введенням звичайних металевих пластин фіксованої товщини у простір між окремими електродами. Дослідний зразок первинного вимірювального перетворювача було досліджено експериментально. Вміст вологи з номінальними значеннями 0, 10, 20 та 30% було відтворено кількома типами зерна з різними значеннями діелектричної проникності: перлова крупа ($\epsilon = 3.68$); мак ($\epsilon = 3.56$); пшоно ($\epsilon = 3.17$); горох ($\epsilon = 2.97$); пшенична крупа ($\epsilon = 2.55$). Експериментальну установку вимірювача вмісту вологи було зібрано з використанням методу заміщення для забезпечення достатньої точності в умовах ємнісних вимірювань у речовинах зі значними діелектричними втратами. Точність вимірювання оцінено як відхил середнього значення вимірюваного вмісту вологи від номінального, а також невизначеність цього відхилу у вигляді невизначеності типу А.

Ключові слова: вимірювання вмісту вологи; зерно; первинний вимірювальний перетворювач; сортова невизначеність методичної похибки; тестовий вплив; оцінка точності.

Первичный измерительный преобразователь влагосодержания для контроля качества зерна

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Аннотация

Целью исследования является разработка емкостного измерительного преобразователя, способного осуществлять тестовые воздействия на исследуемое вещество, реализованные для автоматической компенсации “сортовой неопределенности”, возникающей из-за несовершенства метода измерения. Первичный измерительный преобразователь влагосодержания образован системой электродов в форме V-образных пластин, зафиксированных на внутренней поверхности двух диэлектрических колец.

Опытный образец первичного измерительного преобразователя был исследован экспериментально в совокупности с новым методом определения влагосодержания, который включает два аддитивных, два мультипликативных и два дополнительных тестовых воздействия на исследуемое вещество. Влагосодержание с номинальными значениями 0, 10, 20 и 30% воспроизводилось несколькими типами зерна. Измерительная установка собрана с использованием метода замещения для обеспечения достаточной точности в условиях емкостных измерений в веществах со значительными диэлектрическими потерями. Точность измерения оценивалась как отклонение среднего значения измеренного влагосодержания от номинального, а также неопределенность этого отклонения в форме неопределенности типа А.

Ключевые слова: измерение влагосодержания; зерно; первичный измерительный преобразователь; сортовая неопределенность методической погрешности; тестовое воздействие; оценка точности.

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