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DEVICE FOR MEASUREMENT AND CONTROL OF HUMIDITY IN CRUDE OIL AND PETROLEUM PRODUCTS

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Abstract

A device with a frequency-modulated output signal has been developed to increase the sensitivity and accuracy of measuring moisture content in crude oil and petroleum products in the range of 0~20%. The main element of the device is a self-oscillator transducer based on a transistor structure with negative differential resistance. A capacitive sensor in the form of a capacitive cylindrical structure with cylindrical electrodes was used to determine moisture content in crude oil and petroleum products. Electric permittivity of a two-component mixture of oil and water was estimated and the capacitance of the humidity-sensitive capacitive cylindrical structure with cylindrical electrodes was calculated. An electrical diagram of the device for measuring and controlling the humidity of crude oil and petroleum products has been developed. The relative error of converting the humidity of oil and petroleum products into capacitance which was caused by the change in oil temperature, was determined to be 0.225%. Values of relative errors of the device for measuring the humidity of oil and petroleum products are as follows: $1.355 \cdot 10^{-5}$% is caused by instability of the oscillator frequency, 0.01% is caused by fluctuations in the supply voltage of the self-oscillator transducer, 0.05% is caused by a change in ambient temperature by 1°C. For the developed device, which used errors of the first and second type, the reliability of humidity control of oil and petroleum products has been determined to be 0.9591.

Keywords: crude oil, humidity, moisture content, measurement, sensitivity.

1. Introduction

Measurements of moisture content in crude oil are a key parameter in the extraction of crude oil from wells [1]. The moisture content in crude oil is of great importance for improving the efficiency of oil production and constitutes the main parameter for determining prospects for

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oil field development [2]. Therefore, a timely and accurate measurement of moisture content in crude oil is of great importance for oil production [3]. The measurement of low humidity levels in crude oil is important for monitoring characteristics of an oil well and evaluating the possibility of its enhanced use [4]. Data on a crude oil dehydration are used for calculation of industrial productivity of an oil field as well as economic efficiency of oil production from a specific oil well [5].

Measurement and control of moisture content in crude oil and petroleum products in real time are important in technological processes of oil refining [6]. Results of high-precision measurements of moisture content in crude oil can optimize some production parameters during crude oil refining and increase tar productivity [2]. Measurement of humidity in crude oil and petroleum products is important for reducing costs during transportation and storage [7]. Therefore, the measurement of humidity in crude oil and petroleum products is an urgent scientific and practical task.

Nowadays, many wave methods for measuring the humidity of oil and petroleum products using electronic equipment are known [8]. The basic principle of such methods is based on Maxwell's laws [9]. The moisture content in crude oil and petroleum products, when interacting with radio waves or with an alternating electric current, changes the relative permittivity [10] and specific electrical conductivity [9] in oil and petroleum products. Another approach is to use ultrasonic waves to measure the moisture content in crude oil [11]. This approach is possible due to the fact that the speed of sound in liquids is determined by the state and properties of these liquids [12]. Therefore, at different moisture contents in crude oil the speed of ultrasound will be different [11]. Another variant of the wave method of measuring the moisture content is application of visible optical waves [13]. In [13] a method for measuring the moisture content in crude oil is proposed which is based on visualizing the difference of an accumulated array of crude oil images in a transparent container as grey digital gradations under nominal lighting conditions. This method is characterized by a measurement error of less than 1% with a small power consumption of 165 mW [13].

Other approaches to humidity measurement in crude oil are based on quantum effects of semiconductor materials and require high-cost equipment. Paper [6] proposes a method for determining moisture content of crude oil based on the effect of nuclear magnetic resonance. Paper [14] proposes a non-contact optical method applying a laser emitter that excites laser-induced ultrasonic longitudinal waves in crude oil with moisture content, and a laser receiver with an adaptive laser interferometer. Both methods have high accuracy in measuring the humidity of crude oil.

Capacitive sensors for measuring moisture content in crude oil and petroleum products are the most widespread in industry when various technological processes are being performed [15]. This is because they are easy to implement and are low-cost compared to other microwave devices for measuring and controlling moisture content in crude oil, such as the microwave humidity monitor TMWM, STARCUT [16]. However, capacitive humidity meters have low accuracy and sensitivity. Therefore, to increase the accuracy and sensitivity of measuring moisture content in crude oil, the following methods of signal processing in capacitive sensors have been proposed: a method of cross-correlation of signals using a neural network [10], an amplitude method using a double antenna structure of the receiving antenna, and a coaxial linear phase method of a moisture content meter [2].

The disadvantage of devices for measuring the humidity of oil and petroleum products using capacitive sensors is a low accuracy and low sensitivity. Therefore, the aim of this study is to develop a new microelectronic device with high sensitivity and accuracy for measuring and controlling humidity in crude oil and petroleum products. This device should be low-cost and measure and control humidity in the crude oil and petroleum products that are in a stagnant state in tanks and in a flow state in a pipeline. The device will be useful in various technological processes of extraction, refining, transportation and storage of crude oil and petroleum products.

2. Choice of measurement method and primary sensor development

Sensors that convert the level of humidity into amplitude of an electrical signal have a low sensitivity [4] and accuracy [9]. The sensitivity and accuracy of amplitude humidity sensors can be increased by complicated methods involving computer processing of electrical signals measured [3]. Another way to increase the sensitivity of measuring parameters of physical quantities is to use generator methods [17] and resonance methods [18]. In [19], it was proposed to use the generator method to increase the sensitivity and accuracy of humidity measurement of petroleum products. In [20], we proposed different variants of electrical circuits of measuring transducers based on transistor structures with negative differential resistance. A pyroelectric was used in [20] to implement the optical measurement method. Results obtained after using the optical method for measuring the water content in a two-component water-milk mixture are given in [21] and [22]. As follows from [21] and [22], the optical method for measuring humidity has a lower sensitivity than the generator method.

Modern devices measure the moisture content of crude oil in the range of 0.0% to 20.00%. The values of water mass fraction in crude oil of more than 20% are extremely large, since such crude oil is not suitable for technological processes in oil or chemical industries. For industrial use, the oil with a water mass fraction of more than 20% must be "dried". Examples of modern devices for measuring the moisture content of crude oil using the capacitive measurement method are IVN-3003 with a relative error of no more than 3.0% for the humidity measurement range of 0.50% ~20.00% [23], and FIZEPR-SW100 with a relative error of no more than 5.0% for humidity measurement range 0.0% ~20.00% [24]. Modern devices measure the moisture content of petroleum products in the range from 0% to 100% [24]. This is because different petroleum products utilized in industry (fuel oil, engine oil, used engine oil, burnt diesel, etc.) have different humidity measurement ranges. An example of a device that uses the optical method for measuring the moisture content of petroleum products is RED EYE 2G with a relative error of no more than 2.0% for a humidity measurement range of 0.0% ~100.00% [25]. The WCM 7300M device uses a modified capacitive-differential method that includes the measurement of crude oil temperature [26]. WCM 7300M has a relative error of no more than 1.0% for the crude oil humidity measurement range of 0.0% ~25.00% [26]. The LC2 Phase Dynamics device uses the generator method for measuring the moisture content of crude oil and petroleum products [27]. LC2 Phase Dynamics has a measurement accuracy of ±1% for the crude oil humidity span in a range of 0.0% ~20.00% [27].

Considering the results presented in [21,22], we decided not to apply the optical measurement method. Therefore, we continued the study previously started in [19]. In contrast to [19], in this study we propose to use a capacitive cylindrical structure as the capacitive sensor to measure a moisture content of crude oil and petroleum products. The proposed capacitive cylindrical structure is a system of electrodes, which are made as cylindrical plates of different diameters and fixed in a dielectric tube. The design of the humidity-sensitive capacitive cylindrical structure with cylindrical electrodes is presented in Fig. 1.

The humidity-sensitive capacitive cylindrical structure with cylindrical electrodes operates as follows: when a flow of liquid moves through the dielectric tube, which contains the humidity-sensitive capacitive cylindrical structure with cylindrical electrodes, the liquid fills the space

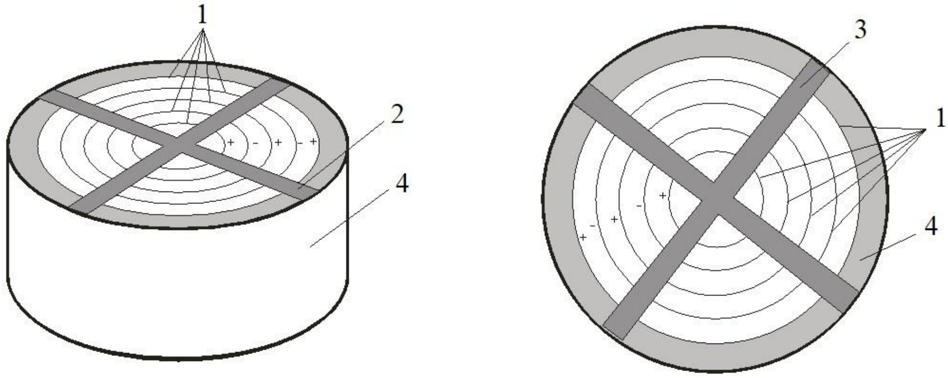

Fig. 1. Humidity-sensitive capacitive cylindrical structure with cylindrical electrodes for measuring humidity of crude oil and petroleum products: general view (left) and bottom view (right). 1 is the system of electrodes; 2, 3 are cross-shaped dielectric electrode clamps; 4 is a dielectric tube. The electrode system 1 is firmly connected by the cross-shaped dielectric electrodes clamps 2 and 3 that are attached to the dielectric tube 4. The length of the electrode system of the humidity-sensitive capacitive cylindrical structure is 40 mm. The outer diameter of the dielectric tube is 50 mm.

between electrodes of positive and negative polarity. These electrodes are rigidly fixed by the cross-shaped dielectric electrode clamps. This causes a change in the electric permittivity, which leads to a change in the capacitance of the cylindrical structure. The Odelevsky empirical equation is then applied to estimate permittivity ε_s of a two-component mixture of oil and water [28]

$$\varepsilon_s = \frac{(3\gamma - 1)\cdot\varepsilon_1 + (3\chi - 1)\cdot\varepsilon_2}{4} + \sqrt{\left(\frac{(3\gamma - 1)\cdot\varepsilon_1 + (3\chi - 1)\cdot\varepsilon_2}{4}\right)^2 + \frac{\varepsilon_1\varepsilon_2}{2}}, \qquad (1)$$

where ε_1 is the permittivity of water; ε_2 is the permittivity of the oil or petroleum product; ε_s is the permittivity of the mixture; γ is the volume concentration of water; χ is the volume concentration of the oil product.

The volume concentration of a petroleum product is determined by the formula

$$\chi = 1 - \gamma. \qquad (2)$$

The volume concentration of water is determined by the formula

$$\gamma = \frac{W\cdot\rho}{(100 - W)\cdot\rho_{H_2O} + W\cdot\rho}, \qquad (3)$$

where ρ is the density of oil or petroleum product [kg/m^3], W is mass humidity [%], ρ_{H_2O} is the density of water [kg/m^3], calculated by the formula:

$$\rho_{H_2O} = \frac{995.7}{0.984 + 0.483\cdot 10^{-3}\,(T - T_0)}, \qquad (4)$$

where T_0 is the temperature that under normal conditions equals 273°K. The expression for a mass humidity W is

$$W = \frac{m_{H_2O}}{m_{\text{mix}}}\cdot 100\% = \frac{m_{H_2O}}{m + m_{H_2O}}\cdot 100\%. \qquad (5)$$

Having substituted in equation (1) expressions for volume concentrations of water (3) and petroleum product (2), we obtained an equation for determining the electric permittivity of the heterogeneous mixture of water and petroleum product for the humidity-sensitive capacitive cylindrical structure with cylindrical electrodes:

$$\varepsilon_s = \frac{\left(\dfrac{3W\cdot\rho}{(100-W)\rho_{\mathrm{H_2O}}+W\rho}-1\right)\varepsilon_1+\left(2-\dfrac{3W\cdot\rho}{(100-W)\rho_{\mathrm{H_2O}}+W\rho}\right)\varepsilon_2}{4} + \sqrt{\left(\frac{\left(\dfrac{3W\cdot\rho}{(100-W)\rho_{\mathrm{H_2O}}+W\rho}-1\right)\varepsilon_1+\left(2-\dfrac{3W\cdot\rho}{(100-W)\rho_{\mathrm{H_2O}}+W\rho}\right)\varepsilon_2}{4}\right)^2+\frac{\varepsilon_1\varepsilon_2}{2}}\,. \tag{6}$$

To calculate the capacitance of the humidity-sensitive capacitive cylindrical structure with cylindrical electrodes, we obtained the following formula:

$$C_w(W,T) = \varepsilon_s\cdot\varepsilon_0\cdot 2\pi\cdot l\cdot\left(\frac{1}{\ln\left(\dfrac{R_4}{R_3+d}\right)}+\frac{1}{\ln\left(\dfrac{R_3}{R_2+d}\right)}+\frac{1}{\ln\left(\dfrac{R_2}{R_1+d}\right)}+\frac{1}{\ln\left(\dfrac{R_1}{R_0+d}\right)}\right), \tag{7}$$

where ε_0 is the permittivity of the vacuum [F/m]; l is the length of the electrode system [m]; d is the electrode thickness [m]; R_0, R_1, R_2, R_3, R_4 are the radii of the electrodes from the smallest one to the largest one [m].

Given expression (6), equation (7) is

$$C_w(W,T) = \left(\frac{\left(\dfrac{3W\cdot\rho}{(100-W)\,\rho_{\mathrm{H_2O}}+W\rho}-1\right)\varepsilon_1+\left(2-\dfrac{3W\cdot\rho}{(100-W)\rho_{\mathrm{H_2O}}+W\rho}\right)\varepsilon_2}{4} + \sqrt{\left(\frac{\left(\dfrac{3W\cdot\rho}{(100-W)\,\rho_{\mathrm{H_2O}}+W\rho}-1\right)\varepsilon_1+\left(2-\dfrac{3W\cdot\rho}{(100-W)\,\rho_{\mathrm{H_2O}}+W\rho}\right)\varepsilon_2}{4}\right)^2+\frac{\varepsilon_1\varepsilon_2}{2}}\right) \times\varepsilon_0\cdot 2\pi\cdot l\cdot\left[\frac{1}{\ln\left(\dfrac{R_4}{R_3+d}\right)}+\frac{1}{\ln\left(\dfrac{R_3}{R_2+d}\right)}+\frac{1}{\ln\left(\dfrac{R_2}{R_1+d}\right)}+\frac{1}{\ln\left(\dfrac{R_1}{R_0+d}\right)}\right]. \tag{8}$$

Having applied the "Maple" mathematical modelling package and according to expression (8), we developed a program for calculating the change in capacitance of the humidity-sensitive capacitive cylindrical structure with cylindrical electrodes caused by the crude oil humidity.

Fig. 2 presents results of calculation and experimental studies of the change in capacitance of the humidity-sensitive capacitive cylindrical structure with cylindrical electrodes caused by the humidity in crude oil of the Turkmen Blend brand in the moisture content range from 0% to 20%.

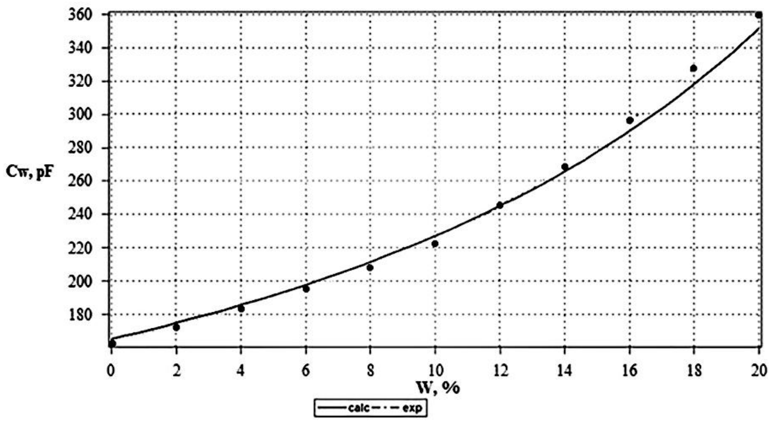

Fig. 2. Experimental data points and graph of the calculated curve of the change in capacitance for the humidity-sensitive capacitive cylindrical structure with cylindrical electrodes from the humidity of crude oil of the Turkmen Blend brand.

3. Development of the device for measurement and control of humidity in crude oil and petroleum products

In [19] we described a system we had developed for measuring and controlling the humidity of crude oil and petroleum products. Its block diagram is presented in Fig. 3.

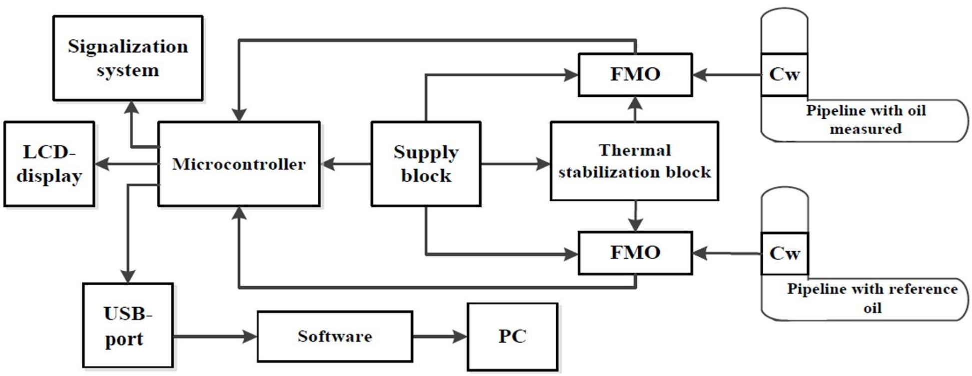

Fig. 3. Block diagram of the system for measuring and controlling humidity in crude oil and petroleum products [19].

The system operates as follows: a change in humidity of the examined liquid leads to a change of capacitance in the capacitive cylindrical structure. The change in capacitance causes a change in the frequency of oscillations at the output of the frequency-modulated oscillator (FMO) based on the negative differential resistance. Then the analogue signal is digitized and the humidity value is displayed on a screen.

The developed device can be used to measure and store values of humidity in oil and petroleum products for a certain time, but also to control an acceptable value of humidity set by the executed program. If the acceptable humidity value is exceeded, an alarm device is activated and a message is displayed that the crude oil or petroleum product does not correspond to the acceptable value (the user sees a “normal” or “abnormal” message on the screen).

The electrical diagram of the device is shown in [19]. The device consists of an 8-bit microprocessor, a quartz oscillator, a power supply, an LCD display. It also contains a thermal stabilization system which consists of the first temperature sensor installed together with the measuring transducer for controlling the humidity of petroleum products and controlling the temperature value within 53°C ±0.5°C. If the temperature becomes less than 52.5°C, a heating element switches on and the measuring transducer of humidity control of oil and petroleum products are heated up to 53.5°C. The second and third temperature sensors are installed on the humidity-sensitive capacitive cylindrical structures to allow for the influence of temperature, namely, to select a specific conversion function from the list of those prescribed in the program at different temperatures.

The device uses the differential measurement method. One capacitive cylindrical sensor is installed in the measuring line with crude oil, and the other capacitive cylindrical sensor is installed in the reference line where the oil has zero humidity. In this way, we excluded the influence of active external factors on the sensors, except for the influence of crude oil humidity. The reference sensor is placed in the oil with zero humidity. We received a reference sample of the oil with zero humidity from representatives of the producing company. For each other type of oil, a corresponding reference oil sample is required.

One capacitive cylindrical structure is installed in the measuring line of a pipeline, and the other capacitive cylindrical structure is installed in the reference line of a pipeline. Information from the measuring transducer controlling the humidity of petroleum products comes (through input nodes) to the microcontroller which measures the frequency of analogue signals and calculates their difference. The value of the difference in the frequencies of these signals by the conversion function (9) stored in the microcontroller memory indicates the percentage of moisture in crude oil and petroleum products. The output signal of the measuring transducer for controlling the humidity of oil and petroleum products is a frequency-modulated signal. This measuring signal has a higher noise immunity to industrial impulse noise of electrical equipment used in various technological processes of extraction, transportation and storage of crude oil and petroleum products [17, 19].

The accuracy of the device is improved by automatic compensation of the systematic error [29]. This automatic compensation includes automatic setting of zero before a measurement starts, automatic calibration operation (self-calibration), self-monitoring, and reducing the impact of random errors by multiple measurements with averaging the results [18, 19].

When performing indirect measurements, the microprocessor system [19]: 1) processes measurement modes automatically in accordance with a specified program, 2) stores the results of direct measurements, 3) performs necessary calculations and displays the physical value measured on a display. Although the measurements are indirect, a user perceives them as direct ones [17–20].

4. Study of metrology characteristics of the device for measurement and control of humidity in crude oil and petroleum products

Fig. 4 shows an approximate conversion function for the measuring transducer. This conversion function is the dependence of the generation frequency of the measuring transducer converter based on a transistor structure with negative differential resistance on the moisture content. The approximate function is

$$f = a + b \cdot W + c \cdot W^2 + d \cdot W^3, \tag{9}$$

where f is the defined parameter (generation frequency); W is the influence parameter (humidity); a, b, c, d are approximation coefficients.

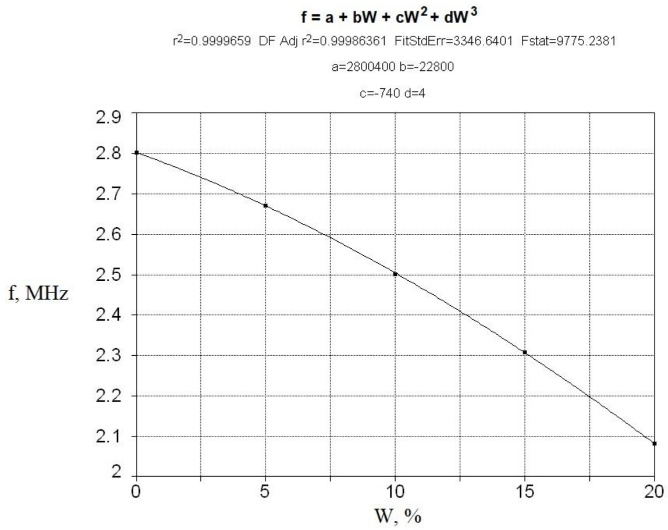

Fig. 4. Approximate dependence of the conversion function of the measuring transducer with capacitive cylindrical structure and cylindrical electrodes for the Turkmen Blend crude oil.

When the humidity-sensitive capacitive cylindrical structure is utilized, the conversion of the non-electric quantity (moisture content of petroleum product) into capacitance causes an error δ_{TCC} due to a change in the temperature of the test substance. This relative error δ_{TCC} shows a change in the capacitance value as a percentage when the temperature changes by 1°C

$$\sigma_{\mathrm{TCC}} = \frac{\Delta T' \cdot \Delta C}{C \cdot \Delta T} \cdot 100\%, \tag{10}$$

where σ_{TCC} is the relative change in the temperature coefficient of capacitance, ΔT is the change in temperature; ΔC is the change in the capacitance of the humidity-sensitive sensor at ΔT in farads; C is the initial capacitance of the humidity-sensitive sensor in farads; $\Delta T'$ is the possible temperature deviation in the system, in °C.

Thus, for the humidity-sensitive capacitive sensor with cylindrical electrodes, the capacitance at $T = 10$°C is 148 pF, and at $T = 100$°C it is 154 pF. Therefore.

$$\sigma_{\mathrm{TCC}} = \frac{5 \cdot (154 - 148) \cdot 10^{-12}}{148 \cdot 10^{-12} \cdot (100 - 10)} \cdot 100\% = 0.225\%. \tag{11}$$

As a result of converting the electrical signal into a frequency-modulated signal, errors occur due to the instability of the self-oscillator frequency σ_1 and fluctuations in the supply voltage of the measuring transducer σ_U and the ambient temperature σ_T. According to experimental results, the measurement error being a result of instability of the generator frequency is $\sigma_1 = 1.355 \cdot 10^{-5}\%$.

To determine the error of a change in the generation frequency due to fluctuations in the supply voltage σ_U, we estimated a change in the generation frequency for a given change in the supply voltage. The electrical circuit of the device utilizes an LM7805 to stabilize the supply voltage. When the LM7805 voltage stabilizer is employed, the standard deviation of the supply voltage at low currents is 5 mV. It corresponds to the change in the generation frequency of 290 Hz.

Therefore, the error of the supply voltage oscillation is

$$\sigma_U = \frac{\Delta f}{f_0} \cdot 100\% = \frac{290 \cdot 100\%}{2800000} = 0.011\%,$$

where Δf is the frequency deviation from the nominal value at a certain deviation of the supply voltage [Hz], f_0 is the carrier frequency [Hz].

The error of ambient temperature fluctuations σ_T is estimated by the formula

$$\sigma_T = \frac{f_T}{f_0} \cdot 100\% = \frac{1450}{2800000} \cdot 100\% = 0.052\%,$$

where f_T is the generation frequency when the ambient temperature changes. According to results of an experiment at the carrier frequency of 2800 kHz, the frequency of 7300 Hz corresponds to a change of 1°C in ambient temperature. When the proposed thermal stabilization is applied, a change in the ambient temperature within 0.1°C is achieved, while the output signal frequency changes by 1450 Hz.

The reliability of measuring the humidity of petroleum products reflects the degree of objectivity of the obtained measurement results in comparison with the true value of the measured value. Instrumental reliability of the control is

$$D_I = 1 - \alpha - \beta, \tag{12}$$

where α is the first-type error; β is the second-type error.

If the first-type error is present, the oil product humidity is considered not to match permissible limits of the value of humidity, although in fact, the oil product meets the requirements (risk of the manufacturer). If the second-type error is present, the oil product humidity is considered to match permissible limits of the value of humidity, although in fact, the oil product does not meet the requirements (risk of the customer).

In this study, the controlled parameter is the value of humidity of crude oil and petroleum products. To calibrate the device, as well as for measuring, we used reference samples of Turkmen Blend brand oil, which have a 0% moisture content. Using these reference samples of the Turkmen Blend brand oil, we created measuring samples of crude oil with different moisture content in a laboratory. To form measuring samples, water-oil emulsions were created with the corresponding mass fractions of water according to the method regulated by the industry standard GOST 2477-2014 [30]. For example, to create the emulsion with a 10% mass fraction of moisture, we mixed 270 g of oil and 30 g of water. We took 100 g of the emulsion to determine the mass fraction of water in oil according to the formula $X = (V_0/m) \cdot 100\%$, where X is the mass fraction of water, V_0 is the volume of water (cm^3), m is the examined emulsion mass (g) [30]. The volume of the evaporated and cooled water in the receiver-trap was 10 ± 0.01 cm^3. The density of the water at room temperature is 1 g/cm^3. Then the numerical value of the water volume in cm^3 corresponds to the mass of water in grams. According to this method, the moisture content of the reference sample was obtained as $10\% \pm 0.01\%$. We utilized the other 200 grams of the emulsion as a reference sample. Having measured with the developed device the humidity of the Turkmen Blend oil with the actual value $W = 10\%$ (Fig. 5), we plotted a histogram of humidity values for the Turkmen oil and of error probabilities (Fig. 6). Here W and ΔW are the intervals of oil humidity and the measurement error, P_W and $P_{\Delta W}$ are the relative frequencies of oil humidity values and the measurement error values that are within the given interval.

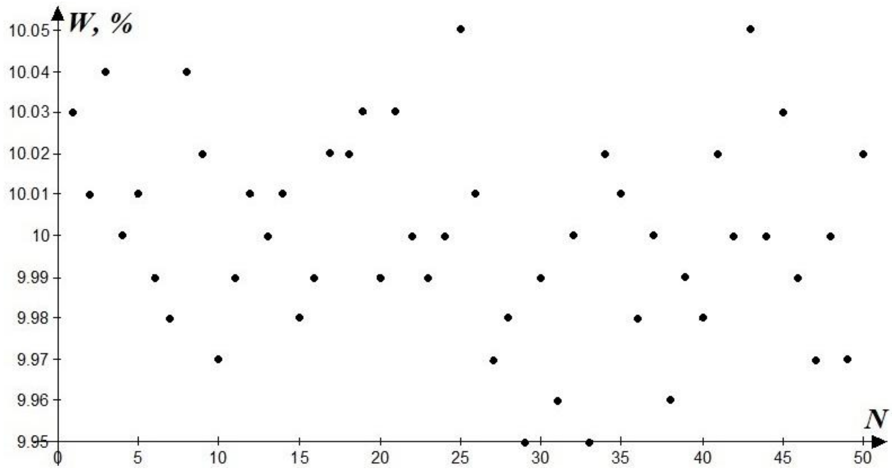

Fig. 5. Graphs of measured values of humidity of the Turkmen Blend brand crude oil.

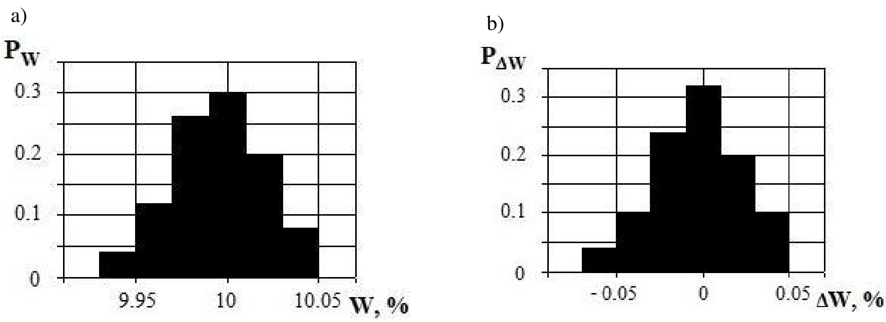

Fig. 6. Frequency histograms: a) probabilities of values of the Turkmen Blend crude oil humidity, b) probabilities of measurement error values.

Values of the crude oil humidity and the measurement errors are distributed according to the normal law and are described by equations

$$f(W) = \frac{1}{\sqrt{2\pi}\sigma_W} \cdot e^{-\frac{(W-\overline{W})^2}{2\cdot\sigma_W^2}}, \tag{13}$$

$$y(\Delta W) = \frac{1}{\sqrt{2\pi}\sigma_{\Delta W}} \cdot e^{-\frac{(\Delta W-\overline{\Delta W})^2}{2\cdot\sigma_{\Delta W}^2}}, \tag{14}$$

where σ_W, $\sigma_{\Delta W}$ are the standard deviations of humidity and the measurement error.

The crude oil humidity values and measurement errors being indeed distributed according to the normal law was verified using Pearson's test χ^2. Accordingly, the first-type and second-type errors are determined from equations:

$$\alpha = \int_{W_A}^{W_B} f(W)\left(\int_{W_A-\Delta W}^{W_A} y(\Delta W)\,\mathrm{d}\Delta W + \int_{W_B}^{W_B+\Delta W} y(\Delta W)\mathrm{d}\Delta W\right)\mathrm{d}W, \tag{15}$$

$$\beta = \int\limits_{W_B}^{W_B+\Delta W} f(W) \left[\int\limits_{W_B-\Delta W}^{W_B} y(\Delta W)\, \mathrm{d}\Delta W \right] \mathrm{d}W + \int\limits_{W_A-\Delta W}^{W_A} f(W) \left[\int\limits_{W_B-\Delta W}^{W_B} y(\Delta W)\, \mathrm{d}\Delta W \right] \mathrm{d}W, \quad (16)$$

where W_A and W_B are the humidity limits of crude oil.

We set the limits of oil humidity tolerance to 0.5%, and the deviation from the actual humidity value ($W = 10\%$) to $W_A = 9.5\%$, $W_B = 10.5\%$. Substituting the given values into equations (15) and (16), we obtain values $\alpha = 0.0283$ and $\beta = 0.0126$. According to expression (12), we obtained the instrumental probability of control $D_I = 0.9591$.

5. Conclusions

The study applied the oscillator-based method of measuring and controlling the humidity of crude oil and petroleum products. The humidity values of oil and petroleum products are converted into the frequency of an electrical signal. This method significantly increases the sensitivity and accuracy of measuring the moisture content in crude oil and petroleum products. To simplify the electrical circuit of the device, reactive properties of the transistor structure with negative differential resistance were utilized. We used the capacitive cylindrical structure with cylindrical electrodes of special design as the humidity-sensitive element.

Static errors of the device for measuring and controlling humidity of crude oil and petroleum products were calculated. The reliability of humidity control of oil and petroleum products on the first and second type errors was estimated. The result was the value of the control reliability $D_I = 0.9591$, which is common for existing means of humidity control. However, the device we have developed is much cheaper.

References

[1] Shi, X., Tan, C., Dong, F., & Escudero, J. (2022). Flow rate measurement of oil-gas-water wavy flow through a combined electrical and ultrasonic sensor. *Chemical Engineering Journal*, *427*, 131982. https://doi.org/10.1016/j.cej.2021.131982

[2] Zhang, L., & Liu, C. (2011). Application of PSO-RBFNN to the prediction of moisture content in crude oil of wellheat metering. *Proceedings of the 2011 International Conference on Computational and Information Sciences*, 571–574. https://doi.org/10.1109/ICCIS.2011.94

[3] Li, K., Xu, W., Han, Y., Ge, F., & Wang, Y. (2020). Soft sensor for the moisture content of crude oil based on multi-kernel Gaussian process regression optimized by an adaptive variable population fruit fly optimization algorithm. *Transactions of the Institute of Measurement and Control*, *42*(4), 770–785. https://doi.org/10.1177/0142331219878959

[4] Guowang, G., Dasen, H., Hua, L., Wang, F., & Li, Y. (2021). Research Status and Development Trend of Water Cut Detection Methods for Crude Oil. *Journal of Physics: Conference Series*, *1894*(1), 012093. https://doi.org/10.1088/1742-6596/1894/1/012093

[5] Xiong, Z. (2018). Simulation, and application of water content determination process of single well crude oil. *International Journal of Simulation and Process Modelling*, *13*(3), 255–263. https://doi.org/10.1504/IJSPM.2018.093115

[6] Yi, L., Ding, J., & Liu, C. (2019). NMR principle analysis based object detection for intelligent measurement of crude oil moisture content. *Proceedings of the 12th Asian Control Conference*, 456–461.

[7] Shengneng, S. (2016). Designing of instruments which detect water content in petroleum products. In N. Qaddoumi, S.-K. Koh, & J. Devlin (Eds.), *MATEC Web of Conferences*, 39, 03007. https://doi.org/10.1051/matecconf/20163903007

[8] Tarasov, B. P., & Kopyl'tsova, A. B. (2013). Assuring the precision of determination of water content by means of laboratory and continuous petroleum moisture meters: Status, problems, achievements. *Measurement Techniques*, *56*(3), 344–349. https://doi.org/10.1007/s11018-013-0207-0

[9] Liu, H., Tang, X., Lu, H., Xie, W., Hu, Y., & Xue, Q. (2020). An interdigitated impedance microsensor for detection of moisture content in engine oil. *Nanotechnology and Precision Engineering*, *3*(2), 75–80. https://doi.org/10.1016/j.npe.2020.04.001

[10] Gao, D., Xiushui, M., Ye, L., Shen, F., & Qiu, C. (2019). Measurement of crude oil water content based on cross-correlation method. *IOP Conference Series: Earth and Environmental Science*, *332*(2), 022033. https://doi.org/10.1088/1755-1315/332/2/022033

[11] Ming, L., Cheng, X., Zhang, L., & Dai, K. (2012). Measurement of water content of petroleum by high accuracy interval measuring chip. *Proceedings of the 4th International Conference on Computational and Information Sciences*, 1171–1174. https://doi.org/10.1109/ICCIS.2012.181

[12] Shafiai, S. H., & Gohari, A. (2020). Conventional and electrical EOR review: the development trend of ultrasonic application in EOR. *Journal of Petroleum Exploration and Production Technology*, *10*, 2923–2945. https://doi.org/10.1007/s13202-020-00929-x

[13] Liu, Q., Chu, B., Peng, J., & Tang, S. A. (2019). A Visual Measurement of Water Content of Crude Oil Based on Image Grayscale Accumulated Value Difference. *Sensors*, *19*(13), 2963. https://doi.org/10.3390/s19132963

[14] Lu, Z. Q., Yang, X., Zhao, K., Wei, J. X., Jin, W. J., Jiang, C., & Zhao, L. J. (2015). Non-contact Measurement of the Water Content in Crude Oil with All-Optical Detection. *Energy Fuels*, *29*(5), 2919–2922. https://doi.org/10.1021/acs.energyfuels.5b00280

[15] Gimson, C. (1989). Using the capacitance charge transfer principle for water content measurement. *Measurement and Control*, *22*(3), 79–81. https://doi.org/10.1177/002029408902200303

[16] Marrelli, J. D., Hatton, G. J., Siddiqui, F., Pepin, L. L., & Helms, D. A. (1992). Continuous determination of oil pipeline watercut, salinity, and API gravity regardless of gas fraction. The microwave watercut monitor. *Proceedings of the International Meeting on Petroleum Engineering*, 16319. https://doi.org/10.2523/22401-ms

[17] Semenov, A., Baraban, S., Semenova, O., Voznyak, O., Vydmysh, A., & Yaroshenko, L. (2019). Statistical Express Control of the Peak Values of the Differential-Thermal Analysis of Solid Materials. *Solid State Phenomena*, *291*, 28–41. https://doi.org/10.4028/www.scientific.net/ssp.291.28

[18] Osadchuk, O. V., Semenov, A. O., Zviahin, O. S., Semenova, O. O., & Rudyk, A. V. (2020). Increasing the sensitivity of measurement of a moisture content in crude oil. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 49–53. https://doi.org/10.33271/nvngu/2021-5/049

[19] Osadchuk, A. V., Semenov, A. A., Zviahin, O. S., Savytskyi, A. Y., Komada, P., & Nurseitova, K. (2019). Numerical method for processing frequency measuring signals from microelectronic sensors based on transistor structures with negative differential resistance. *Proceedings of SPIE*, *11176*, 111765Y. https://doi.org/10.1117/12.2536942

[20] Semenov, A. O., Baraban, S. V., Osadchuk, O. V., Semenova, O. O., Koval, K. O., & Savytskyi, A. Y. (2019). Microelectronic Pyroelectric Measuring Transducers. *4th International Conference on Nanotechnologies and Biomedical Engineering*, 393–397. https://doi.org/10.1007/978-3-030-31866-6_72

[21] Kucheruk, V., Kulakov, P., & Storozhuk, N. (2016). Measurement of the Number Servings of Milk and Control of Water Content in Milk on Stall Milking Machines. *Recent Advances in Systems, Control and Information Technology*, 435–447. Springer International Publishing. https://doi.org/10.1007/978-3-319-48923-0_46

[22] Kucheruk, V., Kulakov, P., Palamarchuk, E., Storozhuk, N., Wojcik, W., Zhassandykyzy, M. (2017). Measuring of the relative milk mass fraction in water-milk solution. *In Przegląd Elektrotechniczny* (Vol. 1, Issue 3, pp. 85–89). Wydawnictwo SIGMA-NOT, sp. z.o.o. https://doi.org/10.15199/48.2017.03.20

[23] Oil product moisture meter IVN-3003 version 2.0. (2018). Retrieved from http://intron-set.com.ua/product/izmeritel-vlazhnosti-nefteproduktov-ivn-3003/

[24] Universal moisture meter FIZEPR-SW100.11. (2022). Retrieved from https://fizepr.com/universal-moisture-meter/specifications

[25] Red Eye®2G. Installation, Configuration, and Operation Manual. (2008). Retrieved from https://skyeye.ca/wp-content/uploads/2013/11/Red-eye-2G-Manual.pdf

[26] Model WCM 7300M Temperature Compensated Water Cut Monitor (2018). Retrieved from http://info.smithmeter.com/literature/docs/SSIN016.pdf

[27] Standalone Water in Hydrocarbon Analyzer. Installation and Instruction Manual. (2006). Retrieved from https://www.skyeye.ca/wp-content/uploads/2013/11/Phase-Dynamice-Installation-and-Instruction-manual1.pdf

[28] Bogorodickij, N. P., Volokobinskij, Yu. M., Vorob'ev, A. A., & Targev, B. M. (1965). *Teoriya dielektrikov*. Energiya

[29] Wójcik, W., Vasilevskyi, O., Kulakov, P., Kompanets, D., Lysenko, O. M., Prysyazhnyuk, V., & Baitussupov, D. (2018). A new approach to assessing the dynamic uncertainty of measuring devices. In R. S. Romaniuk & M. Linczuk (Eds.), *Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments*, *Proc. SPIE*, *10808*, 108082E. https://doi.org/10.1117/12.2501578

[30] GOST 2477-2014. Petroleum and petroleum products. Method for determination of water content. (2016). Retrieved from http://vsegost.com/Catalog/60/60022.shtml

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