Инфокоммуникационные и радиоэлектронные технологии. 2018. Т. 1. № 4. С. 378—388.
Infocommunications and Radio Technologies, vol. 1, no. 4, pp. 378–388, 2018.
ISSN: 2587-9936 print / 0000-0000 online
DOI: 10.15826/icrt.2018.01.4.29

Microwave water content in oil products meter

[1] I. B. Shirokov, [1] I. V. Serdyuk, and [2] I. I. Maronchuk
[1]*Sevastopol State University*
Sevastopol, 299053, Russian Federation
[2]*Genesis-Tavrida Ltd.*
Sevastopol, 299011, Russian Federation
shirokov@ieee.org

Received: September 20, 2018
Peer-reviewed: September 23, 2018
Accepted: September 25, 2018

Abstract: *The paper describes the new method for determining the percentage of water in the water-oil mixture and the manufactured flow-based instrument which uses the microwave communication channel for performing the phase shift measurements with simultaneous evaluation of the degree of absorption of the microwave signal in the test mixture. The results of studies on the justification of operating conditions, development and fabrication of the design of the prototype of the measuring chamber of the device are considered. The results of investigations of the water content in water-oil mixtures of various compositions are presented.*

Keywords: *oil, oil products, water, moisture meter method, water-oil mixture, microwave oscillations, phase progression, microwave signal absorption.*

For citation (IEEE): I. B. Shirokov, I. V. Serdyuk, and I. I. Maronchuk, "Microwave water content in oil products meter," *Infocommunications and Radio Technologies,* vol. 1, no. 4, pp. 378–388, 2018. doi: 10.15826/icrt.2018.01.4.29

УДК 621.317.39.084.2

Микроволновый измеритель содержания воды в нефтепродуктах

[1] Широков И. Б., [1] Сердюк И. В., [2] Марончук И. И.

[1] *Севастопольский государственный университет»*
г. Севастополь, 299053, Росси
[2]*ООО «Генезис-Таврида»*
г. Севастополь, 299011, Россия
shirokov@ieee.org

Получено: 20 сентября 2018 г.
Отрецензировано: 23 сентября 2018 г.
Принято к публикации: 25 сентября 2018 г.

Аннотация: *В работе описан новый метод определения процентного содержания воды в водонефтяной смеси и изготовленный поточный прибор на его основе, базирующиеся на применении микроволнового канала связи для проведения измерений набега фазы с одновременной оценкой степени поглощения микроволнового сигнала в исследуемой смеси. Рассматриваются результаты исследований по обоснованию условий эксплуатации, разработке и изготовлению конструкции опытного образца измерительной камеры прибора. Приводятся результаты исследований прибором содержания воды в водонефтяных смесях различных составов.*

Ключевые слова: *нефть, нефтепродукты, вода, влагомер, водонефтяная смесь, микроволновые колебания, набег фаз, микроволновое поглощение.*

Для цитирования (ГОСТ 7.0.5—2008): Широков И. Б., Сердюк И. В, Марончук И. И. Микроволновый измеритель содержания воды в нефтепродуктах // Инфокоммуникационные и радиоэлектронные технологии. 2018. Т. 1, № 4. С. 378—388.

Для цитирования (ГОСТ 7.0.11—2011): Широков, И. Б. Микроволновый измеритель содержания воды в нефтепродуктах / И. Б. Широков, И. В. Сердюк, И. И. Марончук // Инфокоммуникационные и радиоэлектронные технологии. — 2018. — Т. 1, № 4. — С. 378—388.

1. Introduction

Produced “crude” oil is a multicomponent mixture consisting of oil, gas, and water. The availability of reliable information concerning the oil content makes it possible to judge the profitability of exploitation of the oil deposit [1].

The main oil products derived from oil are the automobile gasolines, the diesel fuel, and the motor oils, which are intensively watered and polluted during transportation, reception, storage, and distribution, with a consequent deterioration in quality. Therefore, the control of water content in oil and oil products is an important task for technological processes at all stages of the extraction, transportation and processing of hydrocarbon raw materials [2, 3]

One of the most popular methods for measuring the water content in oil and oil products are microwave ones. In this case, there are fundamentally two ways for determining the percentage of water in a water-oil mixture. One of them is based on the absorption of microwave oscillations by proper water inclusions [4]. However, this measurement method can give inadequate readings, since the dielectric itself can also absorb microwave oscillations. In addition, with this approach, it is necessary to take measures to stabilize the amplitude of the original microwave oscillations and to ensure the long-term stability of the meter of the transmitted power of microwave oscillations. The presence of conductive impurities in addition to the actual water in the controlled material, for example, ash, salts, etc., provides an additional component of the error in determining the percentage of water in the mixture. In general, in-line microwave hygrometer, when operating in low-watered environments, has a limit of permissible absolute error of ± 0.5% [2, 4]. With an increase in water content up to 60-80%, the phase inversion in the water-oil emulsion is observed, a sharp increase in the resonant frequency occurs, an additional error increases, reflecting on the metrological characteristics of microwave moisture meters [2].

Microwave phase metering methods for controlling the percentage of water in a water-oil mixture give more adequate results [5]. In fact, the relative dielectric constant of most dielectrics lies within 2–4 (about 4 for the vast majority of liquid hydrocarbons). The dielectric constant of water is about 80 (depending on the operating frequency of the analyzer). Therefore, by passing microwave oscillations through a water-dielectric mixture, one can judge the percentage of water in the mixture by measuring the phase shift of the microwave oscillations [5].

However, the described method [5] of determining the percentage of water in the oil-water mixture, when the water content in the mixture varies widely, has one major drawback. The value of phase progression kd [5] depends on the integral dielectric constant of the controlled mixture ε_{mix} and on the layer thickness d of this mixture at the fixed frequency of microwave oscillations. At the same time, with the fixed and unchangeable value of the layer thickness d, the phase progression kd can vary within certain limits in two cases: either when the percentage of water changes (with a known dielectric constant ε_{wat} =

80) in the mixture, or when the electrical properties of the dielectric itself change (dielectric constant ε_{diel}), for example when changing the type of controlled dielectric (crude oil, fuel oil, oil, etc.). The value of the dielectric constant of the controlled product with a change in its type may vary within certain limits (ε_{diel} = 2–4). At the same time, changes in the type of controlled product leads to a change in the integral dielectric constant of the mixture ε_{mix}, which can be interpreted by the meter as a change in the percentage of water in the mixture. When this occurs, the ambiguity of determining the percentage of water in a mixture of oil-water takes place.

In present paper a fundamentally new method of measuring the water content in oil and oil products is discussed. Also in the paper the in-line instrument using a microwave communication channel is described.

2. New method description

In the process of work, a new method for determining the percentage of water in an oil-water mixture was developed. This method is based on the use of a microwave communication channel for measuring the phase progression while simultaneously evaluating the degree of absorption of the microwave signal in the mixture under study. Based on the evaluation of the degree of signal absorption, the percentage of water in the mixture was roughly determined, which made it possible to calculate the number of phase cycles of the microwave signal phase and thereby to determine the exact value of the phase shift, and to calculate the percentage of water in the mixture. The measurement of the phase difference of the signals was carried out at low frequencies, obtained after the homodyne frequency conversion of the microwave signals, which made it possible to obtain high measurement accuracy. Schematic diagram of the device based on the new method is shown in Figure 1.

A device for determining the percentage of water in a oil-water mixture using different dielectrics contains: the microwave oscillator MWO, the microwave directional coupler MDC, the transmitting microwave antenna TMA, the receiving microwave antenna RMA, the controlled microwave phase shifter CPS, the microwave mixer MIX, the low-frequency amplifier LFA, linear amplitude detector AD, phase detector PD, computing device (microcontroller) MCU.

The device that implements the method for determining the percentage of water in the oil-water mixture using different dielectrics operates as follows. Microwave oscillations with amplitude U_1, frequency f_1, and initial phase ϕ_1, described by the following expression

$$u_1(t) = U_1 \cos(2\pi f_1 t + \varphi_1),$$

from the output of the microwave oscillator is fed to the input of the microwave directional coupler. The attenuated microwave signal from the first output of the directional coupler is fed to the input of the transmitting microwave antenna, which primarily emits these microwave oscillations through the layer of the controlled mixture in the direction of the receiving microwave antenna. In this case, the microwave signal acquires the phase progression equal to

$$\Delta\phi = 2\pi f_1 d \sqrt{\varepsilon_{mix}} / c.$$

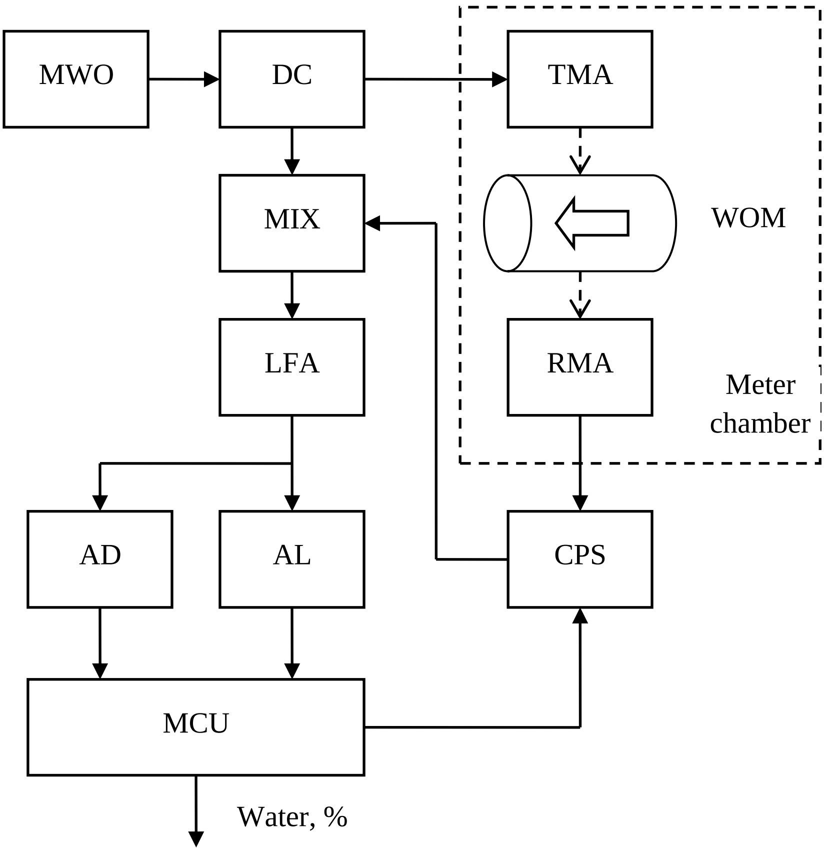

Fig. 1. Schematic diagram of the device based on the developed method.
Рис. 1. Принципиальная схема устройства на основе разработанного метода

Thus, the received microwave oscillations are as follows:

$$u_2(t) = U_1 K \cos\left(2\pi f_1 t + \varphi_1 + \Delta\varphi\right),$$

where $K = K_1 K_2$ is the generalized amplitude factor, K_1 is the attenuation coefficient of the directional coupler on the first output, K_2 is the attenuation coefficient of microwave oscillations in the thickness of the layer of the controlled mixture, taking into account the gain of the microwave antennas.

Next, the received microwave oscillations are fed to the signal input of the controlled microwave phase shifter, to the control input of which a signal generated by the microcontroller is fed as well. In a controlled microwave phase shifter a periodic monotonically increasing from 0 to 2π of phase shift in the microwave oscillations with frequency f_1 is realized. The period of this control signal is equal to $T = 1/F$. In this case, it is possible to speak about the shift of the spectrum of microwave oscillations by the so-called Doppler frequency $F = 1/T$.

Thus, the frequency of the microwave signal is shifted from the frequency f_1 on the frequency F. Frequency-transformed microwave signal with the frequency $f_2 = f_1 + F$ has the following form

$$u_3(t) = U_1 K \cos\left[2\pi\left(f_1 + F\right)t + \varphi_1 + \Delta\varphi + \varphi_2\right],$$

where φ_2 is the initial phase of low-frequency oscillations.

This microwave signal is fed to the second input of the microwave mixer, to the first input of which serves weakened original microwave oscillations with frequency f_1. In a microwave mixer, the multiplication of the microwave oscillations or homodyne frequency conversion takes place. The frequency converted low frequency signal is described by the following expression

$$u_4(t) = U_1 K_\Sigma \cos\left(2\pi F t + \Delta\varphi + \varphi_2\right),$$

where $K_\Sigma = K K_3$ is the total amplitude factor, K_3 is the mixer conversion factor taking into account the attenuation of the microwave signal at the second output of the directional coupler.

This signal is limited in amplitude and is fed to the input of an external interrupt of the microcontroller with the use the integrated Capture-Compare module and Timer. So, the phase difference of the converted signal and the signal generated by the microcontroller itself is measured. The argument of this microcontroller's signal is

$$\Psi = 2\pi F t + \varphi_2 .$$

Thus, at the output of the Capture-Compare module, a digital code COD is obtained, which is proportional to the coefficient K_{PD} of the phase shift of the microwave signal as it passes through the layer of the controlled mixture

$$COD = K_{PD} \Delta\varphi .$$

The number of digits of the received binary code is chosen as much as possible. According to the calibration curve obtained earlier from the calibration results of the meter, the exact value of water content in the oil product is determined in the microcontroller. Moreover, for different dielectrics, with different electrophysical properties, different calibration curves are constructed, each of which is memorized in the microcontroller during the calibration of the meter. Moreover, the calibration curve is chosen that used in the measurements earlier and, if the measurements are carried out for the first time, use, for example, the first memorized in the memory of the microcontroller.

In parallel, the low-frequency signal from the output of the microwave mixer is rectified by a linear detector and the DC voltage is obtained at its output proportional to the attenuation coefficient K_2 of microwave oscillations in the thickness of the layer of the mixture being controlled. This voltage is fed to the input of the analog-to-digital converter built into the microcontroller, where it is digitized.

The conversion process is not used to accurately measure the amount of attenuation of the microwave signal in the thickness of the monitored mixture (not for accurately determining the water content in the dielectric-water mixture), but for roughly estimating the percentage of water content in the oil-water mixture. The more water in the mixture the greater attenuation of the microwave signal takes place. The number of obtained digits is small.

The results of this transformation are compared in the microcontroller within the same number of bits of the binary code with the results of an accurate determination of the water content in a oil-water mixture, which is obtained by the phase method. If these results do not coincide, then this means that a dielectric is chosen that is not with the electrophysical properties that is actually present in the mixture. In this case, the deviation of the dielectric constant of the dielectric selected from the calibration curve from its actual value present in the dielectric mixture is interpreted by the meter as a change in the water content of the mixture, which does not correspond in the first approximation to the water content obtained by the amplitude method. According to the results of the comparison for a given level of water content in the mixture, obtained by the amplitude method in the first approximation, rather rough, choose from the memory of the computing device a curve for which the closest match between the current readings of the analog-to-digital converter and the current level of water content in the dielectric mixture, obtained by phase method, is realized.

It should be understood that discrepancies in the indications of the amplitude and phase methods for determining the water content in a mixture will be observed only for small water content levels, when the contribution of water with the large dielectric constant ($\varepsilon_{wat} = 80$) to the integral dielectric constant of the mixture with the dielectric with the permittivity of $\varepsilon_{diel} = 2\text{-}4$ is small enough. As the level of water content in the mixture increases, the difference in the electro physical properties of dielectrics will be leveled.

4. Measuring camera strength simulation

On the basis of the method obtained, the work was carried out in the field of the development of an experimental in-line instrument. The operation conditions of the instrument can very in a wide range. So, the operation of the measuring chamber of the device in these conditions has to be studied. Consequently, a reasoned choice of materials and the calculation of structural elements of the chamber must be implemented. The calculations were performed using standard techniques used by the oil industry in Russia.

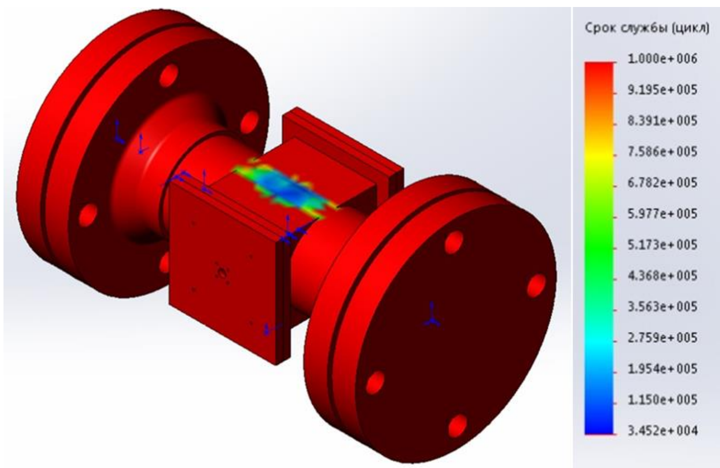

Fig. 2. The diagram of the service life when calculating the fatigue of materials after 1000 load cycles with the calculation parameters: Py = 6.3 MPa, T = 100° C.

Рис. 2. Диаграмма ресурса при расчете усталости материалов после 1000 циклов нагрузки с расчетными параметрами: Ру = 6,3 МПа, Т = 100° С

The strength characteristics of the elements of the developed structure were evaluated using the SOLIDWORKS Simulation software. Studies have shown that under critical operating conditions at a pressure of Py = 6.3 MPa and a temperature T = 100°C, the developed design operates well enough [6]. As an example, Figure 2 shows the plot of the service life when calculating the fatigue of materials after 1000 load cycles with the calculation parameters: Py = 6.3 MPa, T = 100°C.

So, the correctness of the design elements and the choice of materials for their manufacture were confirmed. Studies have shown the load on different parts of the design of the developed device are applied unevenly, while the main load is concentrated in the place of welding of the pipe with opposite segments of the technological measuring channel. Studies on fatigue have shown that for the destruction of this segment, it is necessary to apply at least 34,500 load cycles for the given calculation parameters. The correction of these negative factors with the aim of improving the design features of the working chamber of the device is the goal of further works.

5. Instrument manufacture

Based on the described above studies, the design of an experimental prototype of a microwave measuring instrument for water content in oil products has been manufactured. The microwave primary converter has been designed and manufactured. The microstrip antennas built into the measuring chamber of the device have been designed and manufactured. Also the measuring chamber of the instrument was developed and manufactured.

The appearance of a manufactured measuring chamber with microstrip patch antennas is shown in Figure 3.

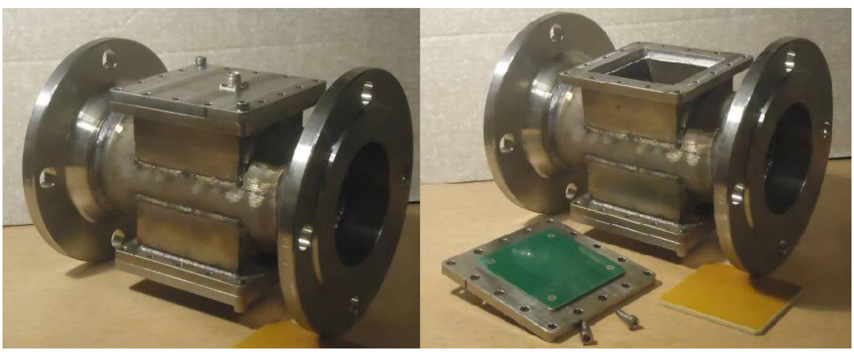

Fig. 3. Appearance of the meter chamber.

Рис. 3. Внешний вид измерительной камеры

The adjustment, calibration and experimental testing of the pilot instrument was carried out on the available crude oil samples with the content of the mass fraction of water in the existing samples being 0.5%, at a temperature of 25° C. When conducting a series of measurements on three prepared samples of "crude" oil, an adequate result was obtained with good compatibility with an average basic error of ±0.08%. Further studies of the water content in water-oil mixtures with a mass concentration of water of 10, 20 and 30% were carried out, the average basic measurement error was ±0.08, ±0.35, ±0.28, and ±0.45%, respectively.

6. Conclusions

The results obtained suggest the use of the new method for determining the percentage of water in the oil-water mixture. On the basis of this method the flow-based instrument has been developed and tested. The method and the instrument are based on the use of microwave communication channel for measuring the phase shift with the simultaneous assessment of the degree of absorption of the microwave signal in the mixture under the test.

Based on the data obtained as a result of research, it is clear that the method presented in the work has an original solution, and an experienced, inexpensive device based on, it has competitive characteristics that make it possible to output and use it in the oil market.

Acknowledgement

The work was carried out as part of the project under contract No. 2200GS1/37052 with the support of the Foundation for Assistance to the Development of Small Forms of Enterprises in the Scientific and Technical Sphere of the Russian Federation.

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Источники финансирования и выражение признательности

Работа выполнена в ходе выполнения договора № 2200ГС1/37052 с Фондом содействия развитию малых форм предприятий в научно-технической сфере.

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Information about the authors

Igor B. Shirokov, Dr. Sci. (Technical), professor at Sevastopol State University, Sevastopol, Russian Federation. ORCID 0000-0001-6425-5385

Igor V. Serdyuk, Cand. Sci. (Technical), associate professor at Sevastopol State University, Sevastopol, Russian Federation. 0000-0001-8988-820X

Igor I. Maronchuk, Cand. Sci. (Technical), leading researcher, Genesis-Tavrida LLC. ORCID 0000-0003-2541-961X

Информация об авторах

Широков Игорь Борисович, доктор технических наук, профессор Севастопольского государственного университета, г. Севастополь, Российская Федерация. ORCID 0000-0001-6425-5385

Сердюк Игорь Владимирович, кандидат технических наук, доцент Севастопольского государственного университета, г. Севастополь, Российская Федерация. ORCID 0000-0001-8988-820X

Марончук Игорь Игоревич, кандидат технических наук, ведущий научный сотрудник ООО «Генезис-Таврида». ORCID 0000-0003-2541-961X