DEVELOPMENT OF A MATHEMATICAL MODEL OF MEASURING CONTROL DEVICE OF NATURAL GAS HUMIDITY

Bilynsky Y., Horodetska O., Novytskyi D., Voytsekhovska O.

1. Introduction

The measurement and control of gas quality parameters is an urgent task of both modern science and its various applications in the national economy. Quality indicators strongly affect the cost of products. Humidity is one of the main parameters in the production, transportation and processing of natural (or associated petroleum) gas [1, 2]. Today, there are a large number of different means of monitoring gas humidity, having a number of disadvantages, namely low accuracy, sensitivity and speed in the entire measurement range [3, 4]. Many methods are already deprived of the possibility of increasing accuracy. Therefore, the problem arises of applying new approaches to significantly improve the quality parameters meters, aimed at increasing their stability, accuracy, sensitivity. To date, methods using the microwave frequency range have gained widespread use due to their simple, reliable design and fairly high measurement accuracy. So, the object of research is the measuring control of the humidity of natural gas. The aim of research is to increase the accuracy of measuring devices for controlling the humidity of natural gas and developing its mathematical model.

2. Methods of research

In [5], the choice of the microwave method for measuring the humidity of natural gas was justified, in which, in contrast to the known methods, the use of a traveling wave in a waveguide is proposed. In this case, changes in the dielectric properties of gases during their interaction with microwave waves are estimated. The essence of the microwave measurement conversion of natural gas moisture is to absorb the microwave signal, and therefore measure the power of this signal at the output of the waveguide when the humidity of the gas changes by using a traveling wave. The authors proposed a mathematical model of such a microwave measuring conversion of natural gas moisture [5]. The conducted studies of the dependence of the traveling wave power on the absolute
humidity of water vapor at various values of the microwave signal transmission length in a humid environment, taking into account temperature and pressure. It is found that with increasing absolute humidity of water vapor, the radiation power decreases according to the exponential law.

3. Research results and discussion

3.1. Block diagram of a measuring device for controlling natural gas humidity. The conducted studies allowed the development of a measuring device for measuring the natural gas humidity (MDGH) based on the microwave traveling wave method, the structural diagram of which is shown in Fig. 1. MDGH is a two-channel and consists of a measuring channel and a comparison channel.

![Structural diagram of a measuring device for natural gas humidity control](image)

MDGH consists of [5]:
- microwave generator 1,
- attenuator 2;
- waveguide tee 3;
- waveguide comparison section (comparative cuvette) 4;
- temperature sensor 5,
- switch comparative channel 6,
- pressure sensor measuring waveguide section 7;
- waveguide measuring section (measuring cell) 8;
- temperature sensor 9;
- switch measuring channel 10,
- attenuators of the measuring channel and the comparison channel 11 and 13, respectively;
- waveguide tee 12;
- diode section 14;
- agreed load 15;
- amplifier 16;
- microprocessor 17;
- analog-to-digital converter (ADC) 18;
- indications 19.

In the moisture measurement transformation, based on the use of the traveling waveguide microwave method, the attenuation is measured, which occurs when the HFEW passes through the gas medium depending on its dielectric constant according to [5, 6] \( K_i = e^{-aL} \), then the HFEW power at the output of the comparison cuvette:

\[
P_i = P_1 - P_2 = \frac{1}{2} K_1 P_0 \cdot e^{-aL},
\]

where \( K_2 \) – the loss coefficient associated with the passage of the waveguide section of the waveguide tee; \( K_9 \) – loss coefficient associated with the HFEW passage through the waveguide section of comparison cell 4 in a vacuum state; \( a \) – the attenuation coefficient of dry air; \( L \) – the length of the comparison cell.

At the signal of the microprocessor 17, the switch comparative channel 6 opens and the HFEW passes to the input of the attenuator 13. When the HFEW passes through the waveguide section of the switch 6, its power \( P_6 \) is attenuated by the amount \( K_8 \) and then, when passing through the waveguide attenuator section 13, by the amount \( K_9 \). Similarly, let’s denote the loss coefficient during the passage of HFEW through the branch of the waveguide tee 12 in \( K_7 \).

The diode in the waveguide section 14 converts the energy of the variable HFEW into direct current \( I_d \), the value of which is proportional to the power of the signal supplied to the input of the waveguide section 14. Let’s denote the conversion coefficient of the diode section \( K_8 \). Then \( I_2 = K_8 \cdot P_6 \), the \( I_2 \) current is supplied to the amplifier 16 at the input of which there is a resistance \( R \) – the coordinated load 15. The resistance \( R \) turns the \( I_d \) diode current into a voltage \( U \), which is amplified by the amplifier 16. The current conversion coefficient of the \( I_d \) diode to voltage \( U \) and the conversion coefficient of amplifier 16 will be designated as \( K_9 \) and \( K_{10} \), respectively. Then the voltage \( U_c \) of the comparison channel at the output of the amplifier 16 is equal to:

\[
U_c = K_9 \cdot K_{10} \cdot I_d = \frac{1}{2} K_5 \cdot K_7 \cdot K_9 \cdot K_{10} \cdot P_0 \cdot e^{-aL}.
\]
3.3. Analysis of the attenuation coefficient. Due to the fact that when HFEW passes through the layer of the gas under investigation, its attenuation directly depends on the properties of the dielectric constant of the gas, it is necessary to consider the effect of the dielectric constant on the MDHGH operation. The dielectric constant of gases depends on temperature. In [7], a formula is given for adjusting the dielectric constant depending on changes in pressure $p$ and temperature $T$ (in degrees Kelvin scale) of the medium under study. The dielectric constant of dry air is $\varepsilon' - 1 = 0.000058$, and $\varepsilon'' - 1 = 0.000058$ [8]. Attenuation coefficient according to [6]:

$$ a = \frac{2\pi K_d}{\lambda} = K_d \cdot Z, $$

where $K_d$ – the attenuation coefficient of dry air, $K_d = f(\varepsilon, \lambda)$ [9];

$\lambda$ – the wavelength that the microwave generator 1 emits, $\lambda = 0.03 \text{ m}; Z = 2\pi \cdot L / \lambda$.

The attenuation coefficient $K_d$ of dry air will vary depending on the temperature in reference cell 4:

$$ K_d = K_2 - K_{11} \cdot t, $$

where $K_{11}$ – the temperature indicator of the attenuation of dry air (takes into account the deviation of the gas temperature in the comparison cell 4 other than 0°C); $K_{11}$ – temperature correction coefficient, for dry air $K_{11} = 0.00000215$ [4];

$t$ – the dry air temperature in the comparison cell (in degrees Celsius).

Accordingly (3) will take the form:

$$ U_i = \frac{1}{2} K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_6 \cdot K_7 \cdot K_8 \cdot K_9 \cdot K_{10} \cdot P_3 \cdot e^{-[K_2 - K_{11} \cdot t] \cdot Z}. $$

3.4. Channel measurement. Let’s consider the operation of the MDHGH measuring channel in the case of filling the measuring cell 8 with an air mixture (hereinafter air), which corresponds to the density and permittivity of natural gas, at a pressure of 1 atm [9]. In this case, the dry air temperature in the comparative cell 4 and the temperature of the controlled air in the measuring cell 8 will be equal.

Indoor air mainly consists of the sum of the attenuation of dry air and water vapor. Therefore, the rate of attenuation of controlled air $K_c = K_d + K_w$, where $K_w$ – is the rate of attenuation of water vapor equal to:

$$ K_w = \frac{1}{\sqrt{2}} \cdot \frac{p \cdot 273.15}{760} \cdot \frac{\rho_w}{\rho_v} \left( \sqrt{(\varepsilon'_w - 1)^2 + (\varepsilon''_w - 1)^2} - (\varepsilon''_w - 1) \right), $$

where $\rho_w$ – absolute humidity of water vapor; $\rho_v$ – water density.

The dielectric constant of water vapor at a temperature of 20 °C is $\varepsilon'_w - 1 = 0.0000619$ and $\varepsilon'' - 1 = 0.0000314$ [4]. It also depends on temperature.

Similarly to (5) and in accordance with [7], let’s make adjustments to the dielectric constant of water vapor depending on the temperature of the controlled air inside the measuring cell 8. The rate of attenuation of dry air, taking into account the temperature adjustment, is known and equal to $K_c$. Therefore, the attenuation rate of controlled air, taking into account the temperature correction $K_w$, will be:

$$ K_c = (K_d - K_{12} \cdot t) + (K_d - K_{11} \cdot t), $$

where $K_{12}$ – temperature correction coefficient, for water vapor $K_{12} = 0.0000036825$; $K_{11} = 0.0000036825$; $t$ – a numerical indicator of temperature in a measuring cell (in degrees Celsius).

Then, by analogy with the operation of comparison channel 4, provided that the design and technological parameters of comparison cell 4 and measuring cell 8, waveguide switches 6 and 10 of the attenuators 11 and 13 are equal, let’s obtain:

$$ U_i = \frac{1}{2} K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_6 \cdot K_7 \cdot K_8 \cdot K_{10} \cdot P_3 \cdot e^{-[K_2 - K_{11} \cdot t] \cdot Z}. $$

The signal $U_i$ is also remembered by the microprocessor 17.

3.5. The mathematical model of the device. When the process of memorizing signals $U_n$ and $U_i$, taking into account the conversion coefficient $K_{11}$, is stored by the microprocessor 17, after which it carries out the logarithm operation. The voltage $U_n$ and $U_i$ is supplied to the analog input of the microprocessor 17, where the ADC 18 with a conversion factor $K_{12}$ is converted to a digital signal $N$. Then the mathematical model of the device can be written as:

$$ \ln \left( \frac{U_i}{U_n} \right) = \ln \left( K_{11} + \frac{2\pi L}{\lambda} (K_d - K_{12} \cdot t) \cdot K_c \right), $$

$$ N_1 = \frac{K_{12} \cdot U_n}{U_{sp}} (2^n - 1), $$

$$ N_2 = \frac{K_{12} \cdot U_i}{U_{sp}} (2^n - 1). $$

where $N_1$ – the binary value of the code of the $n$-bit ADC, which is digitized the voltage $U_n$ of the measuring channel; $N_2$ – binary value of the code of the $n$-bit ADC, digitizes the voltage $U_i$ of the comparative channel; $K_{12}$ – the conversion coefficient associated with the MDHGH calibration.

MDHGH study is conducted. Natural gas consists of 98–99 % methane [10, 11]. The dielectric constant of dry methane is $\varepsilon'_w = 1.000953$ at 0°C [7]. Dry air is pumped into comparison cuvette 4. The dielectric constant of dry air is $\varepsilon'_w = 1.0006258$ at 0°C [7]. It is established that the relative error $\Delta$ in the absence of temperature adjustment and when the air temperature changes from 0°C to 1°C and −1°C leads to an error of ±0.18 %. The values of the correction factors and the relative error in their application are also calculated. It is found that a change in gas temperature relative to 0°C by 1°C and -1°C leads to errors of 0.001 % and 0.000625 %, respectively.

4. Conclusions

A means of measuring control of the humidity of natural gas is proposed, the principle of which is based on the microwave method for measuring the humidity of natural gas, in which, in contrast to the known methods, the use of a traveling wave in a waveguide is proposed. In this
case, changes in the dielectric properties of gases during their interaction with microwave waves are estimated. A mathematical model of the proposed means for measuring the humidity of natural gas has been developed, which takes into account the value of the dielectric constant of the measuring gas and the comparison channel, and contains temperature correction factors, the use of which improves the accuracy of humidity measurement. A study of the measuring channel, the comparison channel, the attenuation coefficient is made, on the basis of which temperature humidity measurements are corrected. The influence of temperature correction factors on the error in measuring humidity is analyzed. Based on the analysis, it can be concluded that the use of these coefficients makes it possible to compensate with high accuracy the difference in the permittivity of dry methane and dry air. The error in this case when the temperature changes from 0°C to 10°C does not exceed 0.01%.

References


Bilynsky Yosyp, Doctor of Technical Sciences, Professor, Head of Department of Electronics and Nanosystems, Vinnytsia National Technical University, Ukraine, e-mail: yosyp.bilynsky@gmail.com, ORCID: http://orcid.org/0000-0002-9659-7221

Horodetska Oksana, PhD, Assistant Professor, Department of Telecommunication Systems and Television, Vinnytsia National Technical University, Ukraine, e-mail: horodecka.os@gmail.com, ORCID: http://orcid.org/0000-0001-6929-1123

Novytskyi Dmytro, Postgraduate Student, Department of Electronics and Nanosystems, Vinnytsia National Technical University, Ukraine, e-mail: yosyp.bilynsky@gmail.com, ORCID: http://orcid.org/0000-0001-6033-406X

Voytsekhovska Olena, PhD, Assistant Professor, Department of Computer Engineering, Vinnytsia National Technical University, Ukraine, e-mail: voytsekhovska.o.v@vntu.edu.ua, ORCID: http://orcid.org/0000-0001-8755-1574