DEVELOPMENT OF SOFTWARE COMPONENT OF THE OPTICAL METHANE CONCENTRATION METER BASED ON LABVIEW

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Abstract

The paper presents a software component and an operation algorithm for an optical methane concentration meter. The software component is developed on the basis of LabVIEW for carrying out experimental studies, which allowed formulating recommendations for improvements of the meter. The implementation of the recommendations made it possible to improve the accuracy of methane concentration measuring by reducing the value of the main and additional errors in the measurement result. Using the developed software component, we established that while performing (6-10) observations in the averaging interval with a sampling period of the output signals of the meter less than 80 msec, the main methane concentration measurement error is not more than 0.1% in the range from 0 to 5%, which is twice less than the regulated value. Using the proposed algorithm for compensating for the temperature drift of the optical meter output signal in the developed software component, made it possible to provide an additional error of methane concentration measurement by not more than 0.2% with temperature changes in the range from +5ºC to + 55ºC. The use of the proposed recommendations in optical gas concentration meters will reduce the probability of explosive situations at enterprises with sudden burst releases of combustible and toxic gases.

Keywords: Methane concentration, Optical meter, Temperature drift, Software component in LabVIEW.

1. Introduction

Usage of optical meters of explosive gas concentration in air gas protection systems at industrial enterprises makes it possible to identify potentially explosive situations in a timely manner [1]. The significant speed of gas dynamic phenomena, complexity and specificity of the conditions in which they occur [2, 3] determine designing low-inertia methane concentration meters with a wide dynamic range. Meters should be insensitive to the effects of the major destabilizing factors of coal mine atmosphere.

Rigid design requirements set for meters in combination with requirements of intrinsic safety have not allowed creating measurement tools so far, providing data about methane concentration changes with small static and dynamic errors. When designing optical meters, it is important to provide regulated accuracy indicators while maintaining the speed of measuring concentration of gas components.

Recently, research priority in the field of information and measurement systems of physical parameters of various environments has been aimed at the creation of adaptive measurement systems.

Currently, a modern application package LabView [4-10] has been widely used; its use in scientific and technical research allows developing adaptive operation algorithms for software components of measurement systems for various applications. This approach allows us to switch from automated monitoring and analysis of measurement results to automatic [4, 5], as well as to solve problems of integration and extrapolation of measurement data in quasi-real-time mode.

Constantly increasing requirements for mining operation safety determine the urgency of conducting continuous research in order to improve computerized means of monitoring parameters of air gas components of mine atmosphere [1]. One of the most effective tools of improving work safety at industrial enterprises is improvement of air gas control systems, which integrate structural elements of hardware and software solutions for measuring concentration of explosive gas components.

Thus, development and implementation of recommendations for improving systems of automatic measurement monitoring and control of optical measurement parameters based on graphic software environments is an urgent scientific and applied task, the solution of which will allow developing a scientific approach to improving mining operation safety.

2. Materials and methods

2.1. Aims and objectives of the study

The aim of the research is development and implementation of compensation algorithms for destabilizing factors of the optical methane concentration meter in the software component of graphic programming LabVIEW to increase accuracy of measurements. To achieve the aim, the following objectives were set and accomplished:

- to develop an operation algorithm for the software component of the optical methane concentration meter and to implement it in LabVIEW;

- to investigate the developed hardware and software component of the optical meter under changing destabilizing factors: reference voltage of the analogue-

to-digital converter, error random component of the measurement result and temperature drift of the meter output signal;

- to estimate effectiveness of the developed and implemented compensation algorithms for the changing destabilizing factors.

2.2. System structure

A block diagram of the developed and designed sample of the optical methane concentration meter is shown in Fig. 1. Zhumeshev et al. [11] and Campo [12] commented that, to create the meter, we used an optocoupler: a lms34LED and photodiode (PD) of the lms36PD type, made in a single technological design with an optical channel (OC) and presented as an optoelectronic sensor. Also, the sensor includes a preamplifier for the photodiode output signal (PA), which converts the PD current signal into a proportional voltage value with its subsequent


amplification.
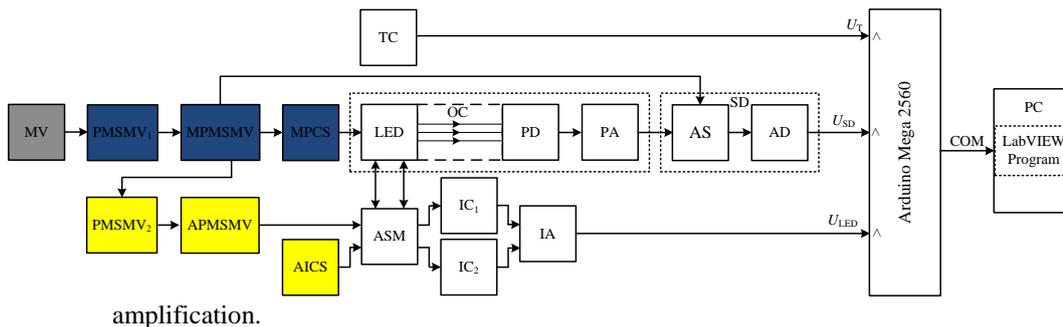
**Fig. 1. Block diagram of the designed optical
methane concentration meter based on LabVIEW.**

During the experimental studies, we established that the minimum self-heating of the LED crystal is achieved at amplitude of additional pulses of 12 mA with their duration of 8.6 μsec at a period, and for master pulses of 2000 μsec. Also, having conducted experimental studies, we found that cooling of the LED crystal to ambient temperature takes place after 60 μsec from the moment of termination of master current pulses, so the pause duration value between master and additional pulses was chosen to be 60.4 μsec. The rectangular pulse sequence is formed by a multivibrator (MV), which generates a meander with a period of 2000 μsec (see 3 in Fig. 2). To eliminate the transient response of the MV output voltage, a pause monostablemultivibrator (PMSMV$_1$) is used, generating pause time (t_{pause1}), the value of which is 60.4 μsec. PMSMV$_1$ output signal is sent to the master pulse monostablemultivibrator (MPMSMV) input, which generates a pulse at its output with duration $t_{pulse\ mast}$=20 μsec to supply LEDs (see 1 in Fig. 2). After master pulse formation, a pause monostablemultivibrator (PMSMV$_2$) is launched between the master and additional pulse sequences, forming the pause time t_{pause2} = 60.4 μsec. To measure LED voltage drop after PMSMV$_2$, an impulse sequence is generated with the help of an additional pulse monostable multivibrator (APMSMV); whose pulse duration is $t_{pulse\ add}$ = 8.6 μsec [13-15].

LED power is supplied from the master pulse current source (MPCS), which, according to MPMSMV signal, generates master current pulses with amplitude of

1000 mA with pulse duration of 20 μsec. The current amplitude for the given pulse duration should not exceed 2000 mA [11]. Simultaneously, MPMSMV sends a signal to an analogue switch (AS) of the synchronous detector (SD) circuit. The analogue key commutes PA output with amplitude detector (AD) input only during MPMSMV signal operation, which allows processing only the master pulse sequence. There is no signal from the additional pulse sequence at ASM input. According to Barret [16], the obtained output signal of SD voltage (U_{SD}) is sent to the analogue (∧) input of Arduino Mega 2560 controller, where it is digitized. Arduino Mega 2560 converts analogue signals (U_{SD} and U_{LED}) into a digital code. Kriftoff [17] explained that, the role of Arduino Mega 2560 is the transmission of digital signals to a personal computer (PC) via COM-protocol into the LabVIEW graphical programming environment. Standard libraries for LabVIEW were specially developed for Arduino Mega 2560 by the National Instrument Company, which allowed optimizing the software development process.
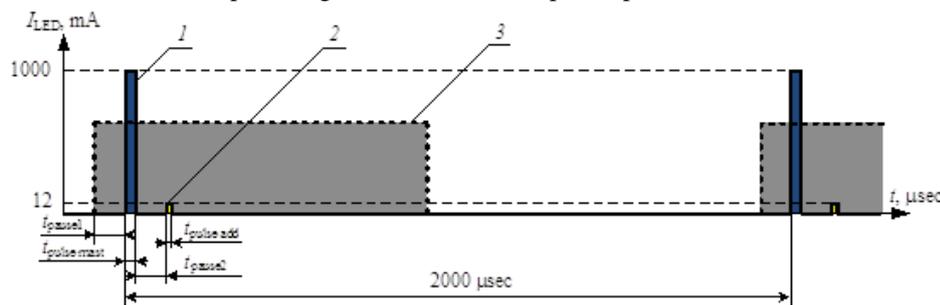

Fig. 2.Timing diagram of master (1) and additional (2) current pulse sequences for LED powering and measuring voltage drop on it, and also setting MV voltage signal (3).

Voltage drop measurement on the LED is taken when additional pulse sequence is applied to it from an additional impulse current source (AICS) [13-15]. After APMSMV signal, the pulse sequence from the AICS, with amplitude of 12 mA with duration of 8.6 μsec, is fed to the LED through the analogue signal multiplexer (ASM). Simultaneously, through the ASM, a voltage drop signal on the LED goes to inputs of integrating circuits (IC_1 and IC_2), which are installed on each of the inputs of the instrument amplifier (IA). That allows processing the voltage drop signal on the LED only during the operation of additional pulse sequence from APMSMV. Output voltage of the IA (U_{LED}), with a value proportional to the LED temperature change, is fed to the analogue (∧) input of Arduino Mega 2560 for implementation of hardware-software compensation method for temperature drift of the meter output signal. A thermistor (TC) of NTC103 type [18] is used for temperature measurement and verification of the temperature drift compensation of the output signal of the methane concentration meter. The thermistor is connected to the voltage divider, and the output signal of the divider (U_T) is fed to the analogue input (∧) of Arduino Mega 2560.

A sample optical methane concentration meter based on LabVIEW was designed and implemented, the photograph of which is shown in Fig. 3. Analogue signals U_{SD} and U_{LED}, as well as digital signal from TC (U_T) are transmitted along the communication lines from the experimental sample of the optical methane concentration meter to the inputs of Arduino Mega 2560. The measurement

information is sent via a USB cable to the PC in the graphical programming LabVIEW, where the information from the optical methane concentration meter is processed, stored and visualized.
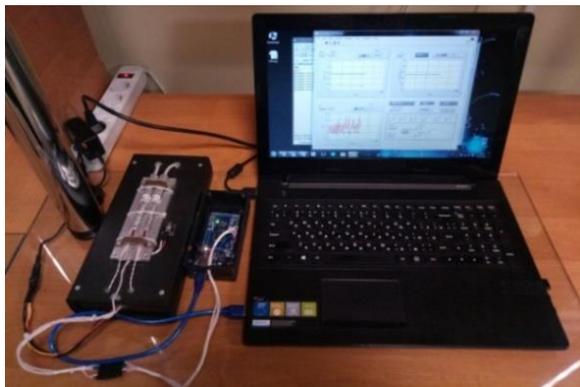
Fig. 3. Photo of the experimental installation.

## 2.3. Method of software component development

Approaches to the study of computerized gas concentration measurement meters that are used in this work are based on modern advances in the theory of information and measurement systems, theories of simulation, physical and mathematical modelling, the probability theory and the theory of mathematical statistics, as well as experimental methods for studying a multichannel meter prototype. The following software was used to implement the main stages of development and research of the optical methane concentration meter: regression analysis of conversion characteristics of the optical methane concentration sensor was performed using MathCad; development and research of the simulation model of the microprocessor system in the Proteus environment (hardware component) and Arduino IDE (software component); processing, visualization and storage of the results of the experimental studies in the LabVIEW graphical programming environment.

Having analysed technical requirements set for the methane concentration meter, we identified functions performed by its software component:

1) initialization of the Arduino module and the components connected to it in LabVIEW;

2) compensation of reference voltage changes in the analogue-to-digital converter (ADC) of the Arduino module;

3) reduction of the error random component of the measuring output voltage in the hardware component of the methane concentration meter;

4) compensation of temperature drift of the optical meter output signal;

5) calculation and indication of the measured methane concentration values.

3. Results and Discussion

Based on the functions performed by the software component of the methane concentration meter, an operation algorithm for the optical meter sample has been developed and implemented, the block diagram of which is shown in Fig. 4.
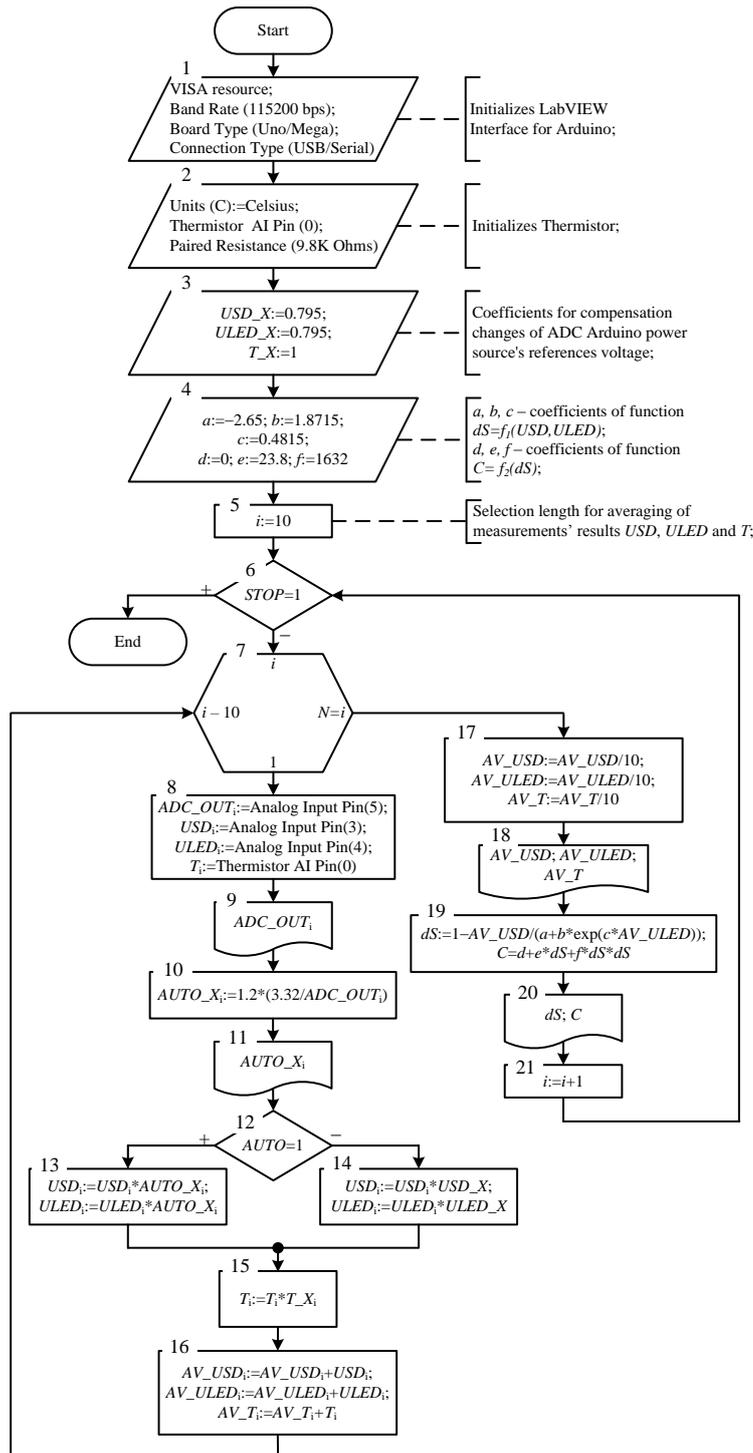
**Fig. 4.Operation algorithm for the software
component of the optical methane concentration meter.**

3.1. Initializing the Arduino module and components connected to it

The LabVIEW initializes connection of the Arduino module with LVIFA interface (see Unit 1 in Fig. 4). Kristoff [17] stated that the interface for Arduino Toolkit can be downloaded at the website of NI LabVIEW. The following modules are used to initialize the Arduino INIT in LabVIEW (see Fig. 5):

1) VISA resource name specifies the resource to be opened, the VISA resource name control also specifies the session and class (Input/Output COM port);

2) Band Rate (115200 bps);

3) Board Type (Uno/Mega);

4) Connection Type (USB/Serial).

For measuring control of ambient temperature, NTC103 type thermistor [18] was used, which was initialized in LabVIEW by Unit 2 (see Fig. 4). Thermistor Read was used to connect the thermistor to LabVIEW via Arduino, which has the following parameters:

1) Unit(C):=Celsius – recalculation of the output value of the measured voltage (U_T) into a temperature signal (T) in degrees Celsius;

2) Thermistor AI Pin (0) – NTC103 thermistor is connected to the analogue ($\wedge$) input 0 Arduino;

3) Paired Resistance (9.8K Ohms) – the thermistor is connected to a voltage divider with pair resistance with the recommended value of 10K Ohms. Having analysed the results of experimental studies of the NTC103 thermistor, we specified the value of the pair resistor in the voltage divider, whose value was 9.8K Ohms.
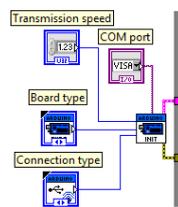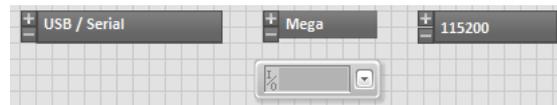
(a) Block Diagram.   **(b) Front Panel.**

Fig. 5. Arduino INIT initialization in LabVIEW.

3.2. Compensation of the ADC reference voltage of the Arduino module

By default, the ADC reference voltage is the Arduino supply voltage. We determined that if the Arduino power is supplied by USB, the ADC reference voltage is significantly affected by the cable length. To eliminate this destabilizing factor, we suggested using a stabilized source of 3.32 V located on the Arduino Mega 2560 board as the reference voltage. To recalculate the ADC output voltage and compensation of the ADC reference voltage change, we developed an algorithm that allows working both in automatic and manual modes (see Unit 12 in Fig. 4).

In the manual mode, values of *USD_X*, *ULED_X* and *T* coefficients are set (see Unit 3 in Fig. 4), which are multiplied by the results of measurements of the U_{SD}, U_{LED} output voltages of the sample optical methane concentration meter (see Unit 14

in Fig. 4) and temperature T (see Unit 15 in Fig. 4). In the automatic mode, *AUTO_X* coefficient is calculated (see Unit 10 in Fig. 4) by reading *ADC_OUT* voltage (see Unit 8 in Fig. 4) from the analogue Pin 5 Arduino to which the reference voltage source 3.32 V is connected. The default ADC digital resolution is:

$$\Delta_{ADC} = \frac{U_{ref\ default}}{2^n - 1} = \frac{5}{2^n - 1} = 4.9\ \text{mV} \tag{1}$$

Taking into account formula (1), the value of the output signal *ADC_OUT* is:

$$ADC\_OUT = \Delta_{ADC} \cdot (2^n - 1) = 4.9 \cdot 10^{-3} \cdot (2^{10} - 1) = 5.013\ \text{V} \tag{2}$$

The signal level (2) can change with the temperature change, as well as under the influence of other destabilizing factors, so we suggested measuring the output signal value *ADC_OUT* (see Unit 9 in Fig. 4) and make corrections to the U_{SD} and U_{LED} voltage measurement results using the *AUTO_X* coefficient, calculated by the formula:

$$AUTO\_X = \frac{U_{ref}}{ADC\_OUT} \cdot K_d = \frac{3.32}{5.013} \cdot 1.2 = 0.7948 \tag{3}$$

The instantaneous value of the coefficient *AUTO_X* calculated according to formula (3) is displayed on the user's screen (see Unit 11 in Fig.4) and, as in the manual mode (see Unit 14 in Fig. 4), is multiplied by the results of the output voltage measuring of the sample of the optical methane concentration meter U_{SD}, U_{LED} (see Unit 13 in Fig. 4).

3.3. Reduction of the random component of the measurement result error

To reduce the random component of the error in the results of measuring U_{SD}, U_{LED} voltages and temperature T, a method of averaging the results of multiple observations was used. Reducing the length of the averaging interval leads to an increase in the basic error of the methane concentration measurement result, which can be the cause of false alarms of measuring equipment due to gross errors in measurement results. The averaging of the results of multiple observations during the output voltage and temperature measurement of the sample optical methane concentration meter is suggested to be performed according to the diagram in Fig. 6.

On the basis of the diagram (see Fig. 6), we obtained formulas for averaging the results of observations of the measured output voltages (4) of the sample and the temperature:

$$AV\_U = \frac{1}{10} \cdot \sum_{i-10}^{N=i-1} U_i \tag{4}$$
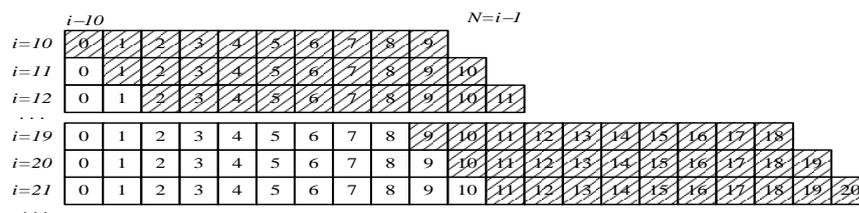
Fig. 6. Diagram of processing the results of multiple observations in measuring the output voltages and temperature of the sample optical methane concentration meter.

The initial value *i* in the processing of the observation results in formula (4) is equal to the maximum number of observations (*N*=10) in the averaging interval (see Unit 5 in Fig. 4). The setting of the sampling period for the output signals of the sample meter is performed in the Delay time block, which is shown in Block Diagram (a) of the software component in Fig. 7. To draw the graphs (see b in Fig. 7) in real time, the Current Time block is used (see a in Fig. 7). To average the results of multiple observations, an infinite cycle is used, the exit of which is performed by pressing STOP button (see Unit 6 in Fig. 4). The transition to the subsequent series of voltage result values and temperature observations, as well as methane concentration measurement results, is carried out by incrementing the variable *i* in Unit 21 (see Fig. 4), which is located at the end of the infinite cycle Unit 6 (see Fig. 4).
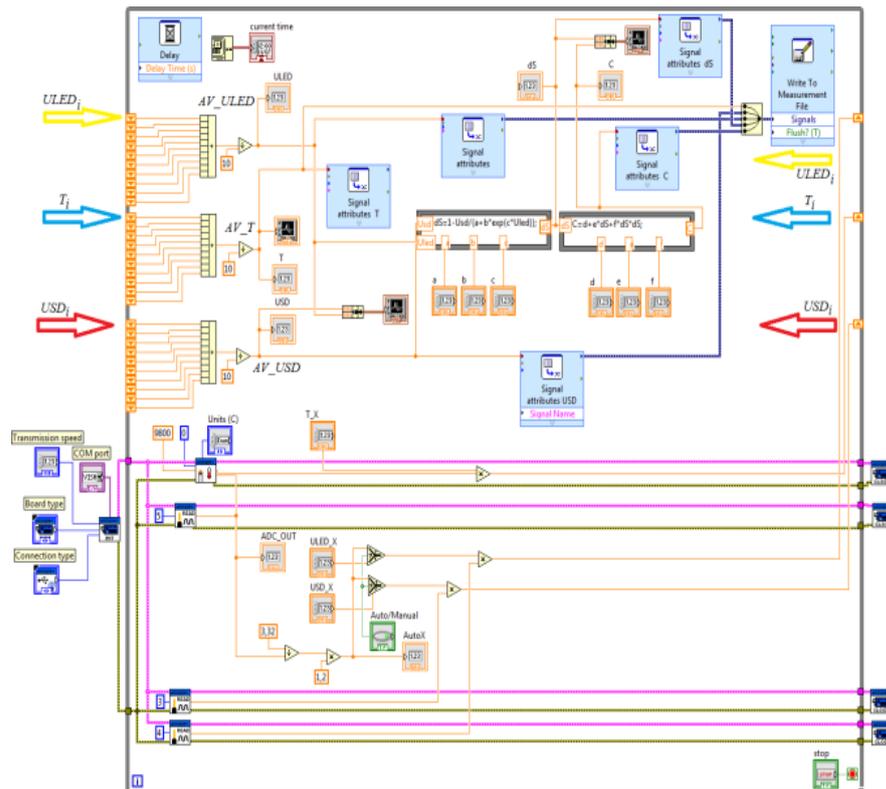
Fig. 7. Block diagram of the software component of the meter in LabVIEW.

Accumulation of *N*=10 observation results is carried out in Unit 7 cycle (see Fig. 4), at the end of which the accumulated observation results of the sample output voltages and temperatures are summarized (see Unit 16 in Fig. 4). After the cycle of observation results accumulation (see Unit 7 in Fig.4), their average values are calculated (see Unit 17 in Fig.4) with formula (4), and also the obtained results are displayed (see Unit 18 in Fig. 4) both in the form of instantaneous values, and in the form of graphs of changes in the meter output voltages and temperature with time (see b in Fig. 7).

3.4. Compensation of temperature drift of the meter output signal

To compensate for the temperature drift of the output signals of the optical methane concentration meter, an appropriate algorithm was developed based on the following idea [13-15]: to use LED as a thermal sensing element of the optical meter, and voltage drop on it, which practically linearly depends on temperature, as an information signal [19]. To implement the developed algorithm, it was suggested to calculate the output signal attenuation level (*dS*) based on the measurement results of the output voltages of the sample meter (*AV_USD* and *AV_ULED*), the value of which is virtually independent of temperature changes (see Unit 19 in Fig. 4) [14, 15]:

$$dS\left(AV\_USD, AV\_ULED\right) = 1 - \frac{AV\_USD}{a + b \cdot \exp\left(c \cdot AV\_ULED\right)} \tag{5}$$

3.5. Calculation and indication of the values of changes in the measured methane concentration

Based on *dS* value, calculated with formula (5), the measured value of methane concentration (*C*) is determined with the formula (see Unit 19 in Fig. 4) [14, 15]:

$$C = d + e \cdot dS + f \cdot dS^2 \tag{6}$$

The results of the attenuation level measuring of the output signal (5) and the target measured methane concentration (6) are displayed (see Unit 20 in Fig. 4) both in the form of instantaneous values and in the form of graphs of the variation of these values in time (see b in Fig. 7).

4. Experimental Results

4.1. Experimental studies of ADC reference voltage compensation

Effect of changing the supply voltage of the Arduino Mega 2560 on the reference voltage value of the stabilized source of 3.32 V [16] was investigated. The Arduino was powered by a USB PC with a nominal value of 5.02 V. To change the power supply voltage, three standard USB cable extensions (USB A – USB M) were used:

- cable #1 with length 1.5 m and voltage drop 0.3 V on it;
- cable # 2: 1.5 m and 0.29 V;
- cable # 3: 1.8 m and 0.04 V.

Results of the experimental studies of reference voltage variations of the source 3.32 V on the supply voltage Arduino Mega 2560 are shown in Table 1.

In order to estimate the value of the additional error in the methane concentration measuring result, by the developed sample with temperature drift of the ADC reference voltage, we carried out experimental studies without using the compensation algorithm for U_{ref} ADC of the Arduino module. The research found (see Fig. 8) that the value of the additional error in methane concentration measurement with changes in the ADC reference voltage in temperature range from +5 to +55 ºC varies from 0.04% (See Fig. 8) to 0.07% (see 3 Fig. 8). Based on studies by Ukrainian Research and Training Center of Standardization, Certification and Quality [20], the obtained values are (20 35) % of the regulated value of the main absolute error of the methane concentration measurement result (±0.20%), which is intolerable and requires elimination.

**Table 1.Variations of the reference source
3.32 V with power supply changes of Arduino Mega 2560.**

| Supply voltage Arduino Mega 2560, V	Value of the reference stabilized source, V	Extension cable connection configuration USB A – USB M
5.02	3.32	**without extension**
4.98	3.32	**cable #3**
4.73	3.32	**cable #2**
4.72	3.32	**cable #1**
4.69	3.32	**cable #3 and cable #2**
4.68	3.32	**cable #3 and cable #1**
4.48	3.32	**cable #1 and cable #2**
4.46	3.32	**cable #3 and cable #1 and cable #2**
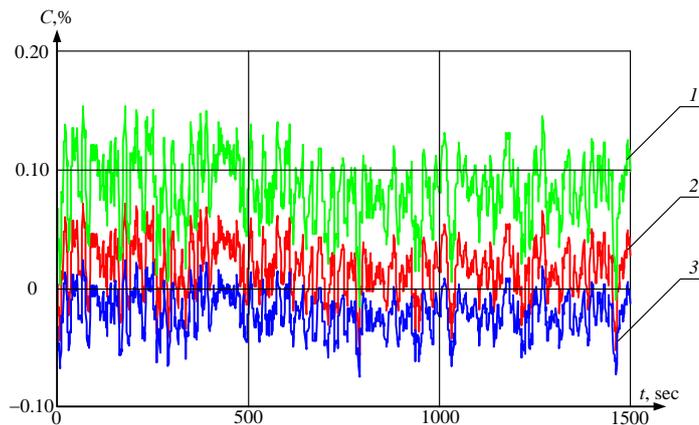
Fig. 8. Output signal of the methane concentration meter at temperature drift of the ADC reference voltage: *1*–U_{ref}=3.315 V at *T*=+5 ºC; *2* - U_{ref}=3.320 V at *T*=+25ºC; *3* – U_{ref}=3.327 V at *T*=+55 ºC.

The coefficient *AUTO_X* is calculated in the software component according to formula (3) for the ADC compensation module. The value of the ADC reference voltage at *T*=+25 ºC is 3.32 V, and as a result of the algorithm the value *AUTO_X* = 0.7948 was determined. With the temperature decreasing to +5 ºC, the value of U_{ref} decreases to 3.315 V, and the value of *AUTO_X* also decreases proportionally to 0.7936. When the temperature rises to *T*=+55 ºC, the value of U_{ref} rises to 3.327 V, while the value of *AUTO_X* also increases to 0.7965. Analysis of the results of the experimental studies has shown that when using the ADC reference voltage compensation module in the software component, the influence of this destabilizing factor is almost completely eliminated.

Having analysed technical characteristics of LP2985-33DBVP voltage stabilizer [21], we found that the possible value of permissible variation in the output voltage is ±3.5% of the nominal voltage 3.3 V at output current from 1 to 50 mA and temperature changes from –40 to +125 °C. The possible value of the acceptable voltage variation in the specified operating conditions of LP2985-33DBVP voltage stabilizer is from 3.204 to 3.436 V. During the experimental studies of the output signal change of the designed meter with the ADC reference

voltage changes (see Fig. 9) in the indicated range, it was discovered that the value of the additional error of methane concentration varies from 1.51% (see 3 Fig. 9) to 3.12% (see 1 Fig. 9). The result obtained (7.6 - 15.6) times exceeds the regulated value of the basic absolute error of the measurement result ($\pm0.20\%$) [20], which is intolerable.
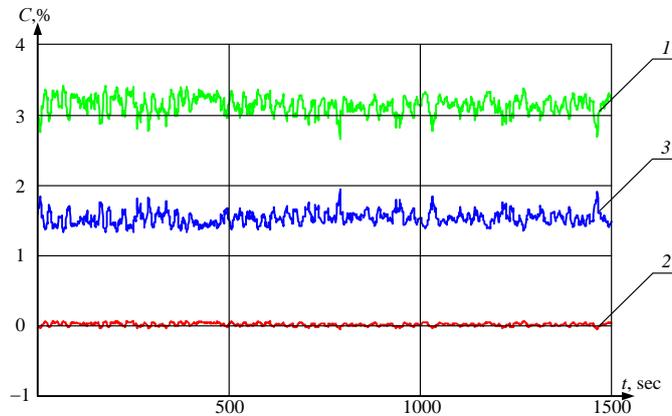
**Fig. 9. The output signal of the methane concentration meter
with the acceptable variation in the ADC reference voltage:
*1 – U*ref=3.436 V; *2 –* ref=3.320 V; *3 – U*ref=3.204 V.**

Based on the results obtained (see Fig. 9), we concluded that methane concentration measurement by the designed sample meter is possible only with account for and compensation of changes in the ADC reference voltage. The nominal value U_{ref} ADC was 3.32 V, for which the correction factor *AUTO_X*=0.7948 was set. With an acceptable variation of −3,5 % of the reference voltage from the nominal voltage to the value U_{ref}=3.204 V, the value of the correction factor is 0.7670, and at 3.5% of the nominal value to the value U_{ref}=3.436 V, the value of *AUTO_X* rises to 0.8226.

The developed and implemented compensation algorithm for the ADC reference voltage changes in the software component virtually eliminates the influence of both the temperature drift of the ADC reference voltage and the acceptable variations in its value from the nominal one. The value of the additional error in methane concentration measurement from the change in this destabilizing factor does not exceed 5% of the basic measurement error ($\pm0.20\%$) [20]. Based on this, it can be concluded that with compensation of the ADC reference voltage, the value of the additional error from the change in this factor can be neglected.

4.2. Decrease in the basic measurement error of methane concentration

To estimate the dependence of the observation number (*N*) in the averaging interval on the value of the error random component, experimental studies of the methane concentration meter output signal were carried out. The number of sampling points was not less than 1500. Figure 10 shows the results of the experimental studies of the output signal of the methane concentration meter at a sampling period of 80 msec: *1* – without compensation of the noise component; *2* – using averaging of the observation results (*N* = 10).
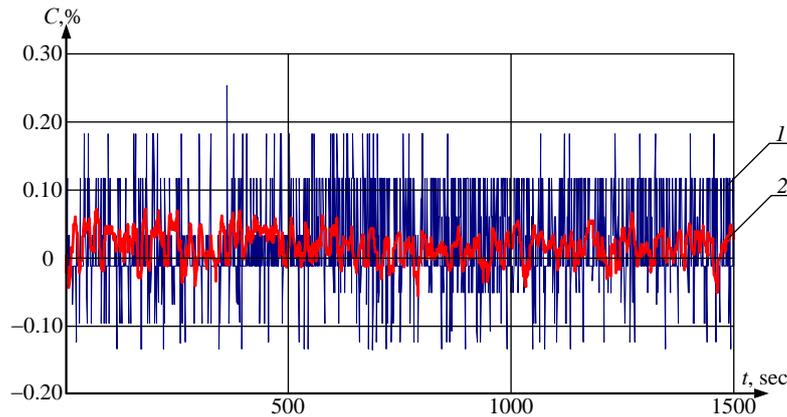
Fig. 10. Changes in the output signal of the methane concentration meter at sampling period of 80 msec without compensation (1) of the noise component and using averaging (2) of the observation results ($N = 10$).

During the experimental studies, a quantitative estimation of the maximum value of the noise component of the meter output signal was obtained. This value corresponds to the maximum value of the basic absolute error of the methane concentration measurement results (Δ_{CH4}) with changes in the number of observations in the averaging interval (N) from 1 to 10 (see Fig. 11), where: $\times$ – experimental studies results.
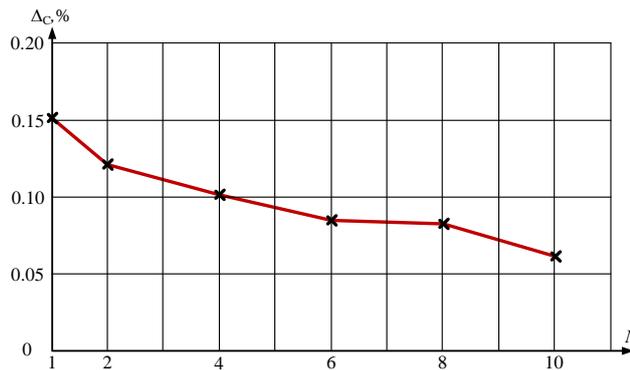

Fig. 11. Changes of the maximum value of the main absolute error of methane concentration measurement results (Δ_C) with changes in the observation number in the averaging interval (N).

Having conducted the experimental studies we found that in order to ensure the value of the basic absolute error of concentration measurement not more than $\pm0.1\%$, which is 2 times less than the value ($\pm0.2\%$) regulated by [20], the required number of observations should be (6 - 10) in the averaging interval. The value of the sampling period for the sample meter output voltage should not exceed 80 msec. This value was established on the basis of the regulated response speed [20] of the methane concentration meter (0.8 sec) with averaging the observation results ($N=10$).

4.3. Study of temperature drift compensation of the meter output signal

During the experimental studies of the designed sample of the methane concentration meter, graduation was performed using a thermostat in the temperature range from +5 to +55 ºC. The value of the additional absolute error in methane concentration measuring in temperature range from +5 to +35 °C should not exceed the basic measurement error (±0.20%) in the range from 0 to 5% [20]. In coal mines, the temperature exceeds +45 °C, so the decision was made to extend the temperature range to +55 °C while maintaining the regulated metrological characteristics of the optical methane concentration meter.

As a result, the dependence of the change in the output signal of the methane concentration meter on temperature changes in the indicated range was obtained (see Fig. 12). Having analysed the results of the experimental studies, we established that application of the proposed compensation algorithm for temperature drift of the meter output signal allows ensuring an additional methane concentration measurement error no more than ±0.15% in the range from 0 to 5%, which does not exceed the regulated value of the main absolute error (±0.20%).
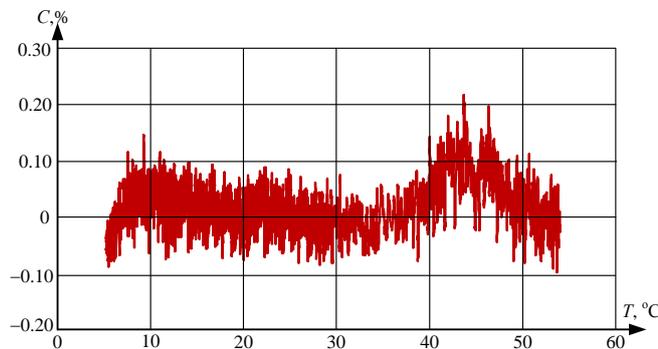

Fig. 12. Changes in the output signal of the methane concentration meter when temperature changes in the range from +5 to +55 ºC.

To verify stability of the sample meter performance, experimental studies were conducted for 4.5 days (105 hours), with methane concentration in the measuring channel of 0%. The results obtained are shown in Fig. 13, where *1* – diurnal temperature fluctuations; 2 and 3, the output signal of the methane concentration meter without and with temperature drift compensation.

During the studies of the sample meter, diurnal temperature fluctuations were from +23.5 to 29.5 ºC. That resulted in variations in the meter output signal value without compensation from 0.05% at $T = +29.5$ ºC to 14.1% at $T = +23.5$ ºC (see 2 Fig. 13). While using compensation, diurnal temperature fluctuations virtually did not change the output signal value of the methane concentration meter. At the same time, the amplitude value of the methane concentration output signal (see 3 Fig. 13) did not exceed ±0.14% at the average value of 0.05%, which is within the regulated value of both the main and additional absolute measurement errors.

The designed methane concentration meter sample showed serviceability both with temperature changes from +5 to +55 ºC, and at the long-term operation. During the experimental studies, the obtained value of the additional methane concentration measurement error did not exceed the regulated value of the basic absolute

measurement error ($\pm 0.20\%$) [20], which fully complies with requirements set for high-speed optical meters operating in the atmosphere of industrial enterprises.
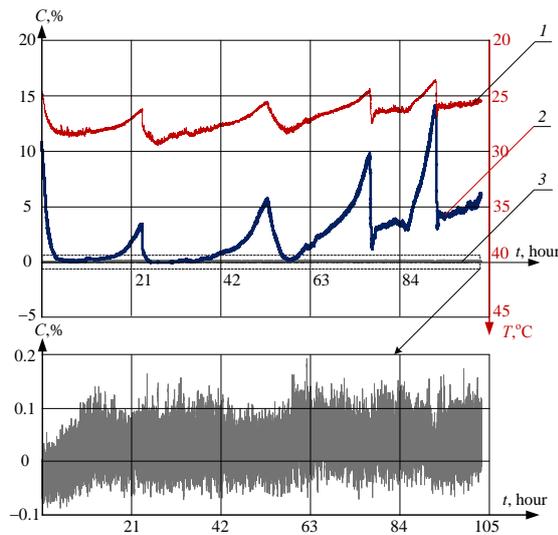
Fig. 13. Results of experimental studies of the meter output signal at 0% methane concentration for 4.5 days (105 hours).

5. Conclusions

The operation algorithm for the optical methane concentration meter was developed, and on that basis the software component in LabVIEW of the sample meter was implemented. The software component was used for conducting experimental studies, which resulted in a set of recommendations for improving accuracy of the methane concentration meter by reducing the value of both the main and additional errors in measurement results.

Reduction of the basic measurement error is effected by reducing the value of the error random component by averaging observation results. During the experimental studies it was established that in order to ensure the value of the main absolute error of methane concentration measurement not more than $\pm 0.1\%$, which is twice less than the regulated value ($\pm 0.2\%$) in the measurement range from 0 to 5%, it is necessary to perform $(6 - 10)$ observations in the averaging interval. In this case, the sampling period of the meter output signals should not exceed 80 msec.

The decrease in the additional error value of the measurement result is performed by taking into account and compensating for changes in the destabilizing factors: the reference voltage of the analogue-to-digital converter and temperature drift of the meter output signal:

- While compensating the reference voltage of the analogue-to-digital converter, the additional methane concentration measurement error does not exceed 5% of the basic measurement error ($\pm 0.20\%$), therefore the value of the additional error with changes of this destabilizing factor can be neglected.

- Application of the proposed temperature drift compensation of the meter output signal makes it possible to ensure an additional methane concentration

measurement error not more than ±0.15% in the range from 0 to 5%, which does not exceed the regulated value of the basic absolute error (±0.20%) and fully meets the requirements set for the optical methane concentration meter.

The method for compensating the temperature drift of the output signal of the optical methane concentration meter has been improved, which allowed us to extend the operating temperature range to +55 °C and to maintain the regulated metrological characteristics. The development of approaches to the creation and technical implementation of new, scientifically grounded results in information and measurement technology made it possible to solve an important applied problem of introducing high-precision high-speed optical meters as a part of the air gas mining operation safety.

The results of the theoretical and experimental research are the basis for the development of high-speed meters that will perform real-time monitoring of concentration of gas components in the atmosphere of industrial enterprises and control technological processes based on the results of gas analytical measurements. Computerized processing of measurement information allowed us to accumulate measurement results and to design adaptive models of extrapolation, as well as to monitor deviations from the technological process based on the monitoring results. The implementation of the proposed recommendations in high-speed optical meters of gas concentration will reduce the probability of explosive situations at enterprises with sudden burst releases of combustible and toxic gases.

Nomenclatures

ADC_OUT	Output voltage of the analogue input pin # 5 of Arduino Mega 2560, V
AUTO_X	Coefficients for compensation changes of ADC Arduino power source's references voltage
AV_T	Result of measuring the output temperature, °C
AV_U	Result of measuring the output voltages, V
AV_ULED, *AV_USD*	Measurement results of the output voltages of the sample optical methane concentration meter, V
a, b, c	Parameters of the function, whose values were established during the calibration of the sample methane concentration meter with temperature changes from +5 to +55 °C
C	Target value of the measured methane concentration, %
d, e, f	Parameters of the function, whose values were established during the calibration of the sample meter with methane concentration changes from 0 to 5%
dS	Attenuation level of the output signal of the optical meter
i	Selection length for averaging of measurements' results U_{SD}, U_{LED} and T
K_d	Transmission coefficient of the voltage dividers that are installed on each of the outputs of the measuring channels of the sample optical methane concentration meter and are used to protect against the ADC input voltages exceeding U_{ref}
N	Number of observations in the averaging interval
n	Effective number of bits for Arduino Mega 2560
T_i	Observation results of temperature at a fixed time interval, which is determined by the sampling period of the measuring channels, °C

T_X	Coefficient for compensation changes of ADC Arduino power source reference voltage U_T
t_{pause1}, t_{pause2}	Generating pause time, μsec
$t_{pulse\ add}$, $t_{pulse\ mast}$	Pulse duration, μsec
U_i	Observation results of output voltages (U_{SD} and U_{LED}) at a fixed time interval, which is determined by the sampling period of the measuring channels, V
U_{LED}	Output voltage of the instrumental amplifier, V
$ULED_i$	Observation results U_{LED} at a fixed time interval, which is determined by the sampling period of the measuring channels, V
$ULED\_X$	Coefficient for compensation changes of ADC Arduino power source reference voltage U_{LED}
U_{ref}	Reference voltage value for the ADC, which is the source of 3.32 V, V
$U_{ref\ default}$	Value of ADC reference voltage, the default value is 5 V, V
U_T	Output signal of the divider, V
U_{SD}	Output voltage of the synchronous detector, V
USD_i	Observation results U_{SD} at a fixed time interval, which is determined by the sampling period of the measuring channels, V
USD_X	Coefficient for compensation changes of ADC Arduino power source reference voltage of the synchronous detector

Greek Symbols

$\varDelta_{ADC}$	ADC digital resolution, mV
$\varDelta_C$	The basic absolute error of the methane concentration measurement results, %

Abbreviations

AD	Amplitude Detector
ADC	Analog-to-Digital Converter
AICS	Additional Impulse Current Source
APMSMV	Additional Pulse MonoStableMultiVibrator
AS	Analog Switch
ASM	Analog Signal Multiplexer
IA	Instrument Amplifier
IC	Integrating Circuits
LED	Light Emitted Diode
MPCS	Master Pulse Current Source
MPMSMV	Master Pulse MonoStableMultiVibrator
MV	MultiVibrator
OC	Optical Channel
PA	PreAmplifier for the photodiode output signal
PC	Personal Computer
PD	PhotoDiode
PMSMV	Pause MonoStableMultiVibrator
SD	Synchronous Detector
TC	Thermistor
USB	Universal Serial Bus

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