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High-speed optical methane concentration meter with the dust compensation of mine atmosphere

We tested an optical-absorption methane concentration meter for coal mines conditions. We studied conversion characteristics and evaluated its speed performance and proposed a method of dusty coal mines air multiplicative compensation. Requirements to the development of a methane concentration meter are provided.

keywords: meter, speed performance, multiplicative compensation, conversion characteristics, tests.

1. GENERAL STATEMENTS

The increase in gas-dynamic manifestations in coal mines atmosphere leads to the necessity of developing new and improving existing facilities of methane concentration control. Thus we can take into account the drawbacks of existing gas-analyzers and meet the international standards for gas concentration meters development. Our development is related to analytical measuring of gas components concentrations, mainly in the dusty atmosphere, and can be used in measurement and air- gas control systems at industrial enterprises and in environmental monitoring.

2. RESEARCH PROBLEMS

The paper is aimed at the perfection of gas concentration meters on the basis of optical-absorption control method through the development of the method and its hardware implementation.

To achieve the aims it is necessary to solve the following problems:

– to develop an optical-absorption methane concentration meter with mine air dust compensation;
– to define experimentally the meter conversion characteristics;
– to test the effectiveness of dusty coal mines air multiplicative compensation method used in methane concentration measurements;
– to determine speed performance.

3. PROBLEM SOLUTION

State Higher Education Establishment "Donetsk National Technical University" in cooperation with the Private Company "Data Express" (Donetsk, Ukraine) designed and developed mockup sample of a high-speed optical-absorption meter methane concentration for coal mines. The methane meter block diagram is shown in figure 1 [1, 2]. When making a methane concentration meter we used light-emitting diode LED34 (as radiation source RS_1) and photodiode PD36 (as photodetector PDR) We took into account mine air circulation through the optical channel (OC_1) measuring cell. To obtain the required value of methane concentration measurement absolute error (less than 0,2 $^{vol.}$%) [3] in dusty coal mines atmosphere we developed and studied the method of multiplicative compensation of mine air dustiness [4, 5], which was implemented on the basis of a dual channel meter. With the purpose of hardware implementation of this method we introduced an additional compensational OC_2 with RS_2 – the LED LED29 and PDR_2 – the PD PD36 [4, 5].

For power supply of measuring (RS_1) and compensation (RS_2) LED we used a current source (CS) controlled by voltage. The block diagram of controlled current source for LED power supply is shown in figure 2, where LED is a light emitting diode, CS is a current source controlled by voltage; PS is power supply; VR is a reference voltage source; S is a switch; $CTRS_{CS}$ is a CS control signal from the microcontroller. LED is connected directly to the current source. VR output voltage is continuously adjusted by an output voltage divider, and it provides continuous adjustment of LED feed current amplitude. LED feed current pulse sequence is formed by control signals from the microcontroller ($CTRS_{CS}$) through the analog switch, which provides the LED pulse mode.

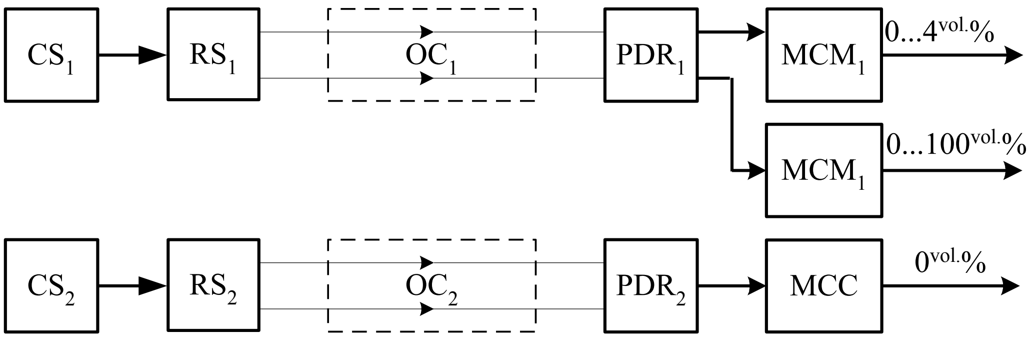


Fig. 1. Methane concentration meter block diagram

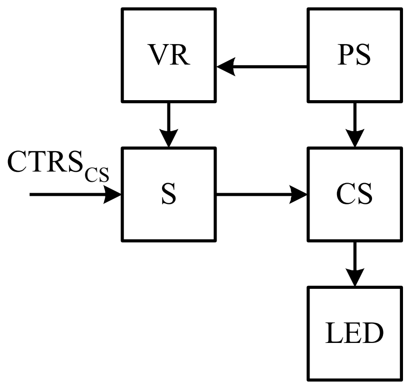


Fig. 2. Block diagram of the current source for LED supply

The block diagram of measuring (MCM) and compensation (MCC) channels of the methane concentration meter is shown in figure 3. To provide the photovoltaic mode of PD PD36 operation we used the transimpedance amplifier (current to voltage converter) – photodetector (PDR). The preamplifier (PA) of the output signal PDR increases the signal amplitude up to the level required for normal operation of the amplitude detector (AD). AD (taking into account the integration constant) converts the output pulse sequence amplitude of PA into DC voltage signal the value of which is proportional to the measured methane concentration. AD output signal comes to the normalizing converter (NC), which performs an additional low-pass filtering of AD output signal, and scales it with providing ADC input level.

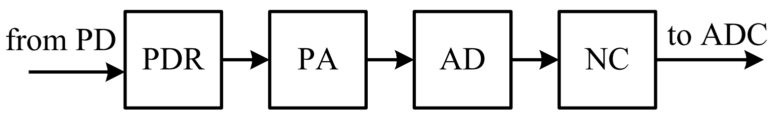


Fig. 3. Block diagram of measuring (MCM) and compensation (MCC) meter channels

While designing a methane concentration meter we formulated the requirements for the following units:

1. Current source for LED supply:
- grounded load;
- load current rectangular pulses;
- current pulses amplitude variation range, from 1,4 to 1,6 A;
- current pulses repetition frequency, 2 kHz ;
- period of current pulses repetition, 500 μs;
- current pulse duration range, from 10 to 20 μs;
- pulse front duration, less than 2 μs;
- pulse recession duration, less than 3 μs;
- control voltage amplitude from the microcontroller U^0_{Ctrl}, plus (0,3…0,4) V; U^1_{Ctrl}, plus (4,8…4,9) V;
- supply voltage, U_S, ±9 V;
- power supply voltage instability, ±0,1%.

2. The analog channel of the methane concentration meter:
- PD current amplitude variation range, from 0,4 to 0,8 μA;
- PD mode close to the short circuit;
- maximum potential difference across PD, less than 1 mV;
- PDR operational amplifier with the field-effect transistors with p-n-transition on the inputs (FET input);
- linearity of PDR transmission characteristics;
- minimum level of PDR noise;
- maximum input PDR current, less than 10 pA;
- minimum value of PDR output voltage amplitude, less than 0,5 V;
- PDR passband, less than 1,0 MHz;
- variation range of AD input voltage amplitude, from + 2,5 to + 4,0 V;
- AD maximum output voltage, less than +7,5 V;
- NC output voltage range, from +0,2 to +4 V;
- NC passband, less than 10 Hz;
- supply voltage, U_S, ±9 V;
- power supply voltage instability, ±0,1%.

The methane concentration meter was tested in the laboratory of Petrovsky Coal Engineering Plant. Laboratory tests were performed using calibration gas mixtures (CGM) in the balloons of the following types: (1,30 ± 0,15) %; (2,51 ± 0,08) %; (4,30 ± 0,15)%; (97,0 ± 0,5) %. The characteristics of methane concentration meter conversion were defined by measuring the average output voltage of measuring channels (MCM and MCC) in the process of gas mixtures supply from CGM balloons in a closed measuring cell. The measurement results are shown in table 1.

Table 1.

The measurements results of the methane concentration meter conversion characteristics

Methane concentration, C_{CH4}, vol.%	The average value of the meter output voltage, U_{OUT}, V		
	№ 1	№ 2	№ 3
0	0,01	0,005	0,003
1,30	0,24	–	–
2,51	–	0,406	0,398
4,30	0,52	0,540	0,522
97,0	15,4	16,01	–

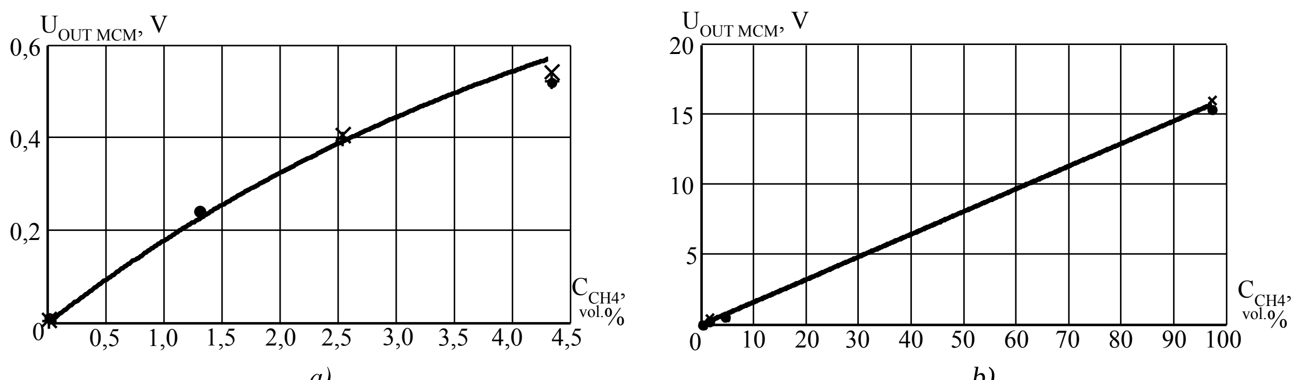


Fig. 4. Conversion characteristics of methane concentration meter in the range: a) from 0 to 4,3 vol.%; b) from 0 to 97,0 vol.%

Figure 4 shows experimentally obtained conversion characteristics of the meter which correspond to measurements ranges a) from 0 to 4,3 vol.% [6] and b) from 0 to 97 vol.%. In figure 4: •– № 1; × – № 2; + – № 3 – measurements series; ——— – approximation results of the conversion characteristics.

The sensitivity of the methane concentration meter is in the following ranges :

– from 0 to 4,3 vol.%:

$$S_{CH4} = \frac{\Delta U_{OUT\ MCM}}{\Delta C_{CH4}} = \frac{0{,}552 - 0{,}003}{4{,}3 - 0} = 0{,}128\,\frac{\text{V}}{^{\text{vol.}}\%};$$

– from 0 to 97 vol.%:

$$S_{CH4} = \frac{\Delta U_{OUT\ MCM}}{\Delta C_{CH4}} = \frac{15{,}4 - 0{,}003}{97 - 0} = 0{,}159\,\frac{\text{V}}{^{\text{vol.}}\%}.$$

The conversion characteristic of the meter are almost linear in the range of methane concentrations from 0 to 4,0 vol.% and from 0 to 97 vol.%. The sensitivity of the meter in the range of methane concentration from 0 to 4,3 vol.% is 0,128 V/vol.% and in the range from 0 to 97 vol.% it is 0,159 V/vol.%.

To verify the method of multiplicative compensation of atmosphere dustiness we defined conversion characteristics MCM and MCC of the meter when the following values change: methane concentration changes from 0 to 4,3 vol.%,, and the optical radiation transmittance coefficient changes from 1,00 to 0,30 in the wave range from 2,5 to 4,0 μm. When conducting laboratory tests we used special films with different optical radiation transmission coefficients: 100 %; (90±1) %; (50±1) %; (30±1) %. To test the method efficiency we defined the information output signal component Mux which is proportional to methane concentration with coal dust effect compensation, as an output voltage - measuring channels ratio:

$$\text{Mux} = \frac{U_{OUT\ MCM}}{U_{OUT\ MCC}},$$

where $U_{OUT\ MCM}$ and $U_{OUT\ MCC}$ are MCM and MCC measuring channels output voltage of the meter.

Table 2 shows the results of meter laboratory tests with optical density variation of dust and methane concentration. Figure 5 shows the meter conversion experimental characteristics, which correspond to different values of dust optical density and methane concentrations: experimental values of meter conversion characteristics with coal dust optical density variation: + – 100 % (0 mg/m^3); □ –90% (158 mg/m^3); ◇ – 50 % (1039 mg/m^3); ○ – 30% (1805 mg/m^3); ——— – the results of conversion characteristics approximation.

Table 2.

Meter conversion characteristics with optical density variation of dust and methane concentration

C_{CH4}, vol.%	$U_{OUT\ CM}$, V	Transmittance coefficient, T, % (coal dust concentration, C_C, mg/m^3)			
		100 (0)	90 (158)	50 (1039)	30 (1805)
0	$U_{OUT\ MCM}$, V	1,00	0,90	0,50	0,30
	$U_{OUT\ MCC}$, V	1,01	0,90	0,51	0,30
	Mux	0,99	1,00	0,98	1,00
1,30	$U_{OUT\ MCM}$, V	1,24	1,10	0,61	0,35
	$U_{OUT\ MCC}$, V	1,02	0,89	0,50	0,29
	Mux	1,22	1,24	1,22	1,21
2,51	$U_{OUT\ MCM}$, V	1,41	1,23	0,70	0,41
	$U_{OUT\ MCC}$, V	1,03	0,89	0,51	0,30
	Mux	1,37	1,38	1,37	1,37
4,30	$U_{OUT\ MCM}$, V	1,52	1,37	0,77	0,47
	$U_{OUT\ MCC}$, V	1,01	0,91	0,51	0,31
	Mux	1,51	1,51	1,51	1,52

From the analysis of conversion characteristics (shown in figure 5), it follows that the developed method of coal mines atmosphere dustiness multiplicative compensation helps to eliminate the component conditioned by coal dust presence in the measuring channel. Consequently, when developing a meter we should use a dual-channel optical system, which will take into account and compensate for the influence of one of the main destabilizing factors in the mine atmosphere (coal dust influence), and thus we can obtain the required metrological characteristics of the meter.

We propose the methods of defining the meter performance and a device for their implementation which employs a rotating disk with a hole. It has 100% optical radiation transmittance coefficient. With the variation of disk drive rotation frequency we defined the duration of transition process when measuring channel output voltage was 0.9 of the established value. For this purpose we used a measuring oscilloscope. The duration of the transition process was defined by the following expression:

$$t_{TR} = \sqrt{t_{TR\,M}^2 + t_{TR\,CSS}^2}\ ,$$

where $t_{TR\,M}$ is the duration of the transition process at setting the methane meter output voltage; $t_{TR\,CSS}$ is the duration of the transition process of the meter speed performance control system (the time of the overlap of the optical beam with a rotating disk).

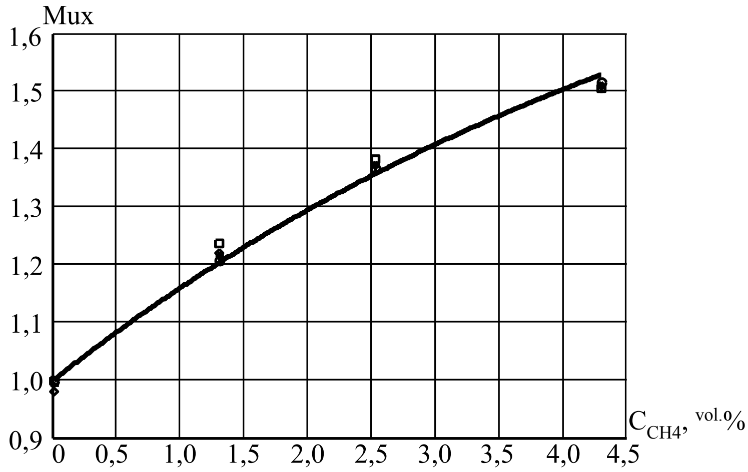


Fig. 5. Conversion characteristics of methane concentration meter taking into account mine air dustiness compensation (Mux)

The laboratory tests results of the meter speed performance are shown in table 3. Figure 6 provides the graph of transition process duration at setting the output voltage from the disk rotation frequency. With the increase of disk rotation frequency the transition process duration $t_{TR\,CSS}$ decreases in comparison with $t_{TR\,M}$ and its contribution to the total transient time is also reduced. The experiments showed that with disk rotation frequency over 2,0 Hz transition process duration (when methane concentration is being measured with the developed meter) is 53 ms, at the same time the contribution to the overall transition process $t_{TR\,CSS}$ is small (see figure 6). The theoretical calculation of the transient process duration on measuring channel transition function is 47 ms [1, 2] and that almost agrees with experimental results.

Table 3.

Laboratory tests results for meter speed performance

Disk aperture change period, *T*, s	**Disc rotation frequency, *f*=1/*T*, Hz**	**Transition process duration at setting the output voltage, t_{TR}, ms**
2,00	0,50	59,0
1,00	1,00	55,4
0,67	1,49	54,1
0,50	2,00	53,3
0,40	2,50	53,0

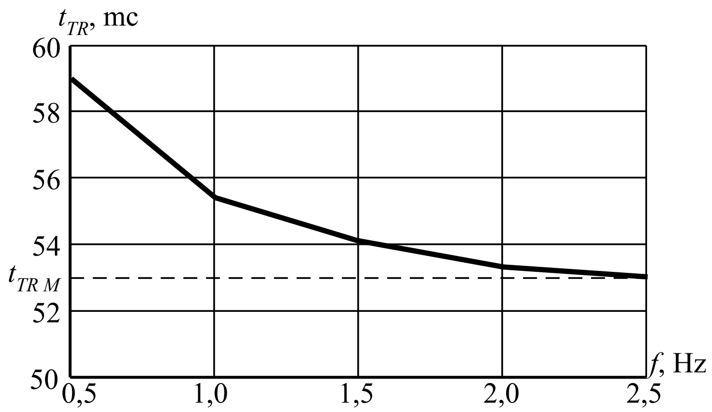
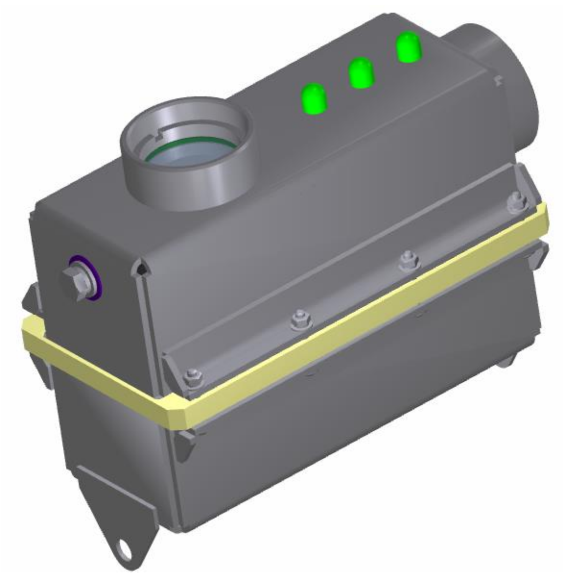


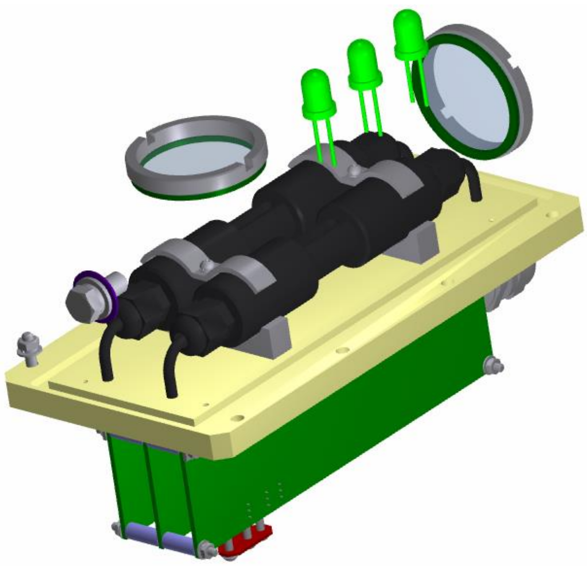
Fig. 6. The change of transition process duration from disk rotation frequency (f)

Consequently, the speed performance of the developed meter is less than 0,06 s when the maximum permissible methane-meter response time is 0,8 s, this time was defined according to state standard [3].

At designing a high-speed optical methane concentration meter the model sample casing design was developed, which exterior is shown in Fig. 7 (a), and construction of casing design without safety covers in Fig. 7 (b).



a)



b)

Fig. 7. Case exterior of methane concentration meter model sample (a) and its design concept without protective covers (b)

The meter consists of two sections: section with optoelectronic components and a section with electronic converters. The electronic part is connected to a telecommunication cable with aerogas protection system of coal mine. On the section case of the optoelectronic components there are LED indicators for qualitative measuring mapping of the methane concentration. The meter is installed under the arch of mine working roof supports of coal mine downward LED indicators.

Natural circulation of air flow is provided in the construction through the optoelectronics meter section. The air intake is located on the opposite side of the meter in relation to the air flow to prevent the meter clogging from dust. The authors have proposed to use a woven mesh, whose grid size is approximately 0.04 x 0.03 mm, to extend the recalibration interval, and improve metrological reliability of the meter. Using the mesh at the inlet of the air intake provides a degree reduction of turbulence in the air flow, which could substantially reduce the dustiness of the meter optical components. The dust air mixture flow after passing through the optical channels exits through an outlet located below the meter and circulates the gas environment, and controls the dust rests removal.

The investigations that were conducted confirm the possibility of meter applying for methane concentration control in mine air with a dust concentration of about 1 g/m^3.

4. CONCLUSIONS

1. A methane concentration meter was developed and tested. We tested the meter in the laboratory of State Enterprise "Petrovsky Coal Engineering Plant" and came to the conclusion that:

– the meter conversion characteristic is practically linear in the range of methane concentrations from 0 to 4,0 $^{vol.}$% and from 0 to 97,0 $^{vol.}$%, the meter sensitivity in methane concentrations range from 0 to 4,3 $^{vol.}$% is 0,128 V/$^{vol.}$% and in the range from 0 to 97 $^{vol.}$% it is 0,159 V/$^{vol.}$%;

– the meter speed performance is less than 0,06 s with maximum permissible response time of methane meters about 0,8 s , which was defined according to state standard [3]. It confirms the efficiency of the given method in controlling the methane concentration in coal mines.

2. A method of mine air dustiness multiplicative compensation and its hardware implementation was proposed. Laboratory tests proved the effectiveness of the developed method, which removes the error component conditioned by the presence of coal dust in the optical measuring channel.

3. The technical requirements to a high-speed methane concentration meter were formulated. Further development of gas components concentration analytical measuring instruments presupposes designing an experimental meter, which is to be tested in laboratory and mine conditions. The development and introduction of experimental meters in the system of air-gas protection is planned.

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