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Methane Emission Estimation Tools as a Basis for Sustainable Underground Mining of Gas-Bearing Coal Seams

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Abstract: Underground coal mining of gas-bearing coal seams is accompanied by the emission of large amounts of methane, which increases with depth. Coal seam methane is not only a major cause of major accidents in coal mines, but is also a greenhouse gas that has a significant negative impact on the Earth's atmosphere. Analysis of the efficiency of underground coal mining suggests that as the depth of mining increases, the productivity of a longwall decreases by a factor of 3–5 or more, while the specific volume of methane emitted increases manifold and the efficiency of methane management decreases. Effective management of coal seam methane can only be achieved by monitoring its content at key points in a system of workings. Monitoring of methane not only eliminates the risk of explosions, but also lets us assess the effectiveness of using methane management techniques and their parameters to improve efficiency and reduce the cost of methane management (including a methane drainage) for ensuring sustainable underground coal mining. The aim of this article is to develop a software and hardware complex for monitoring methane in a coal mine by creating a simulation model for monitoring methane. The Arduino Uno board and the methane sensor MQ-4 were used for this purpose. In this article, the causes of methane emissions in coal mines, gas control systems, the structure of the mine monitoring system, and the causes of risks and occurrence of accidents in coal mines are considered. As a result of the work, the mathematical model of the methane measurement sensor was developed; the Arduino Uno board developed a simulation system for methane monitoring; and the numerical results of the research are presented in the graphs.

Keywords: coal mine; coal seam methane; environmental management; sensors; monitoring systems; Arduino; diagnostics

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Citation: Sidorenko, S.; Trushnikov, V.; Sidorenko, A. Methane Emission Estimation Tools as a Basis for Sustainable Underground Mining of Gas-Bearing Coal Seams. *Sustainability* **2024**, *16*, 3457. https://doi.org/10.3390/su16083457

Academic Editor: Chaolin Zhang

Received: 22 February 2024
Revised: 11 April 2024
Accepted: 17 April 2024
Published: 20 April 2024

1. Introduction

Coal has long been a significant source of primary energy in the world. In the near future, the major industrialized countries of the world, countries with emerging markets and economies in transition will depend on coal-based energy resources. Coal supplies now cover 25% of the world's primary energy demand, 40% of global electricity demand and almost 70% of global steel and aluminum energy demand. According to International Energy Agency projections, in emerging markets, energy demand will increase by 93% by 2030; this is mainly due to increased demand in China and India, and coal may become the main energy source, which will meet growing demand [1,2]. However, as reserves were depleted, coal plaques had to be worked out at deep depths with a high gas content in less favorable geological conditions, owing to the continued dependence of enterprises on solid fuel. At the same time, the rest of society demanded and wished to improve the safety of mining conditions and to show greater environmental responsibility for the coal industry [3,4]. Best practices for reducing the frequency of methane-related accidents and explosions—which all too often accompany underground coal mining—include the application of best practices in methane source drainage, refining and recovery; this could also help to protect the environment by reducing greenhouse gas emissions [5–7]. Recently, methane has gradually become the subject of research due to its significant contribution to the greenhouse effect. On a 20-year time scale, the global warming potential of methane was 86 times greater than that of carbon dioxide [8,9]. As a result, reducing methane emissions is an effective strategy to slow the rate of climate warming in the short term, and a necessary means to meet the temperature targets of the Paris Agreement [9–11].

Mining companies seek to minimize the likelihood of accidents, especially those related to methane explosions. In order to ensure the economic impact of the extraction and sale of raw materials, it is necessary to ensure safe and continuous production. This includes effective risk management. Despite the differences in geological and mining conditions, there are opportunities to significantly reduce the risk of accidents at enterprises mining gas-bearing coal seams [1,12,13].

Safety in the event of accidents and catastrophes is one of the main tasks of the ventilation systems.

As a result of the accident, the ventilation system of the shaft shall provide:

(1) Prevention of the gases' spread into the mine;
(2) Quick and reliable change of direction of ventilation jets;
(3) Prevention of formation of dangerous concentrations of explosive gases [4,14,15].

Specialized methane monitoring systems were needed to address the problems encountered in the development of gas-bearing coal seams. At that time, the monitoring systems in place in many coal mines were ineffective, as evidenced by the high number of accidents [16,17]. It is necessary to predict the risk of occurrence of dangerous physical processes, which will ensure the effective, uninterrupted operation of the enterprise. Table 1 summarizes quantitative data on the main causes of accidents.

Table 1. Classification by types of accidents at Russian coal mines [18–20].

Main Causes of Accidents	Average Annual Number of Accidents	Proportion (%)
Sudden outbursts of coal or gases	137	39
Destruction and landslides, accidents in the faces and in the places of mining	112	32
Underground fires	71	21
Sparks and flash fires	9	3
Accumulation and collapse of water	4	1
Methane explosion, coal dust explosion	4	1
Other reasons	12	3

Table 1 shows that a large number of accidents are related to sudden outbursts of coal or gases, sparks and flash fires. In addition, a significant share is related to underground fires. These data indicate that mine atmosphere monitoring, observations and analysis of physical processes are underutilized. Therefore, the aim of the research is to develop a software and hardware complex for monitoring methane in a coal mine [21,22].

Table 2 shows the largest fatal coal mine accidents in the world over the last 20 years. More than 55% of accidents are caused by accumulation of methane.

Thus, the main task of the research can be formulated as follows: the development of a hardware–software complex of methane monitoring in a coal mine. To develop this, it is necessary to solve the following tasks:

Table 2. Largest coal mine accidents in the world over the last 20 years [23,24].

Sl No.	Year	Country	Mine Name	Accident Cause	Fatality
1	2004	Russia	Tayzhina	Accumulation of firedamp	47
2	2004	Ukraine	Donbass	Accumulation of firedamp	36
3	2005	China	Shenlong Mine	Accumulation of firedamp in the shafts to reach the density of explosion and wire sparks induced the blast	83
4	2006	China	Lin Jiazhuang Coal Mine	Explosion in a sealed of area due to not using explosion-resistant seals	54
5	2006	India	Bhatdee Colliery	Accumulation of methane due to incomplete stowing and high amount of coal dust generation, leading to explosion	50
6	2006	México	Pasta de Conchos Mine	Accumulation of methane	65
7	2006	Kazakhstan	Mittal's Lenin	Accumulation of methane	41
8	2007	Ukraine	Zasyadko	Accumulation of methane	101
9	2007	Russia	Yubileynaya	A pocket of methane gas exploded as methane drainage was not done	39
10	2007	Colombia	Norte de Santander	Accumulation of methane followed by roof fall	32
11	2007	Russia	Ulyyanovskaya	Accumulation of firedamp due to deliberate disabling of a methane detector by the mine management to avoid costly work stoppages	108
12	2009	China	Heilongjiang Mine	Inadequate ventilation leading to accumulation of methane	108
13	2009	Indonesia	Sarana Arang Sejati	Accumulation of methane with suspected source of ignition being cigarette lighter/generator spark	32
14	2010	Russia	Raspadskaya Mine	Buildup of methane in an unventilated tunnel	90
15	2010	Colombia	San Femando	Accumulation of methane	73
16	2011	Pakistan	Sorange Mine	Accumulation of methane and mine collapse	52
17	2012	China	Xiaojiawan Coal Mine	Accumulation of methane and carbon monoxide poisoning	47
18	2013	China	Babao Mine	Gas leakage from seals induced explosion	53
19	2014	Turkey	Soma Coal Mine, Manisa	Accumulation of methane, fire and carbon monoxide poisoning	301
20	2015	Ukraine	Zasyadko	Accumulation of methane	33
21	2016	Russia	Vorkuta Mine	Accumulation of methane	36
22	2016	China	Jinshangou Coal Mine	Accumulation of methane	32
23	2017	Iran	Zemestan-Yort Mine	Accumulation of methane and spark generated due to powering of a locomotive using an external battery	42
24	2021	Russia	Listvyazhnaya	Accumulation of methane	51
25	2023	Kazakhstan	Kostenko	Accumulation of methane	46

1. Analyze the existing technologies of the coal mines' methane concentration monitoring. To choose and adapt the technology, taking into account the peculiarities of the mine selected as the subject of the study.
2. To develop a hardware–software complex of methane monitoring. The peculiarity of the developed device should be the possibility of spatial diagnostics, which allows real-time monitoring of methane passage along the shaft of a coal mine.
3. To collect the information from the coal mine and build models for predicting the concentration of methane in the mine [25–28].

The solutions of these tasks allows expansion of the possibilities of diagnostic devices' application to other areas of the coal industry.

2. Materials and Methods

Following is a description of the technological process. The mining industry de facto includes both underground and open pit methods, or a combination of both. The underground coal mining industry is a mine and the open mine is a mine [29,30]. As of

2022, there are 160 coal-producing enterprises in Russia, including 107 open pit mines and 53 underground mines [2,31].

Almost all work in coal mines is performed by special machines, which differ from each other in many parameters. The choice of special equipment depends on the physical condition of the mined rock [32,33]. In underground coal mining, shearers are mainly used. These cut a coal seam and grind the coal. The destruction of the coal mass is affected by the mechanical properties of coal seam and rock, the thickness and depth of a seam, the gas content, the advance rate, etc. Currently, more than 90% of underground coal production in Russia is carried out with the use of a longwall mining method. The division of the coal seam is carried out by ventilation and transport workings. At the same time, the increased reliability and energy efficiency of coal mine treatment equipment has increased the productivity of coal mines under favorable mining and geological conditions. The most common technology is the retreat mining system, which uses fully mechanized longwall mining [34,35].

Intensive longwall mining is accompanied by a constant increase in the depth of mining operations, which leads to deterioration of mining geological conditions; above all, the frequency of dangerous manifestations of rock pressure increases, as does methane abundance of mine workings, which increases the risk of accidents [36–38].

Methane is an explosive gas that presents a hazard in 5–15% of the Voc-Spirit concentrations. Transport, collection or treatment should occur at concentrations not more than 2.5 times below its lower limit or not more than twice its upper limit, because of the explosive nature of methane at such concentrations.

The practice of safe mining at coal-bed methane mining facilities aims to reduce the risk of methane explosion by preventing the occurrence of explosive mixtures and their early dilution to non-hazardous concentrations (using ventilation systems and schemes). Pre-drainage of coal seams is also used [39–41].

At present, most of the work of miners is taken over by automatic and automated systems, so there is more and more self-propelled equipment in the mines.

The categorization of gas mines comprises the distribution of coal mines into different hazard levels, which are determined by the level of gas present in coal mines and in mines in general. Underground coal mines are classified by methane content [42].

In the first category, the volume emitted is up to 5 m^3/t. The second category implies the presence of methane in sizes from 5 to 10 m^3/t. In the third category, methane content ranges from 10 to 15 m^3/t. The fourth category (considered to be a supercategory) implies the methane content of the mine greater than 15 m^3/t or the presence of sulfur gas emissions. The fifth category is defined as mines with non-hazardous coal and gas emissions. Mines with coal outburst and methane emissions are classified in the sixth category. Figure 1 shows the division of coal mines by methane content [2,43,44].

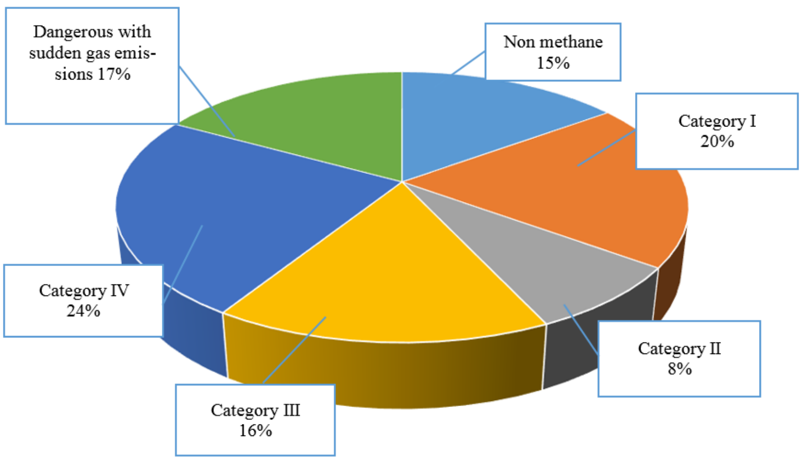

Figure 1. Distribution of coal mines with different methane content. Source: Compiled by the author.

The productivity of the longwalls is constantly increasing. In that context, the quality requirements for the preparation and development of mining projects and the implementation of occupational safety requirements were being met. Mining planning should be given a greater role, as often the multiple coal seams influence on each other are mined, resulting in a redistribution of rock pressure and a change in the methane content of the formations as they are mined [45–47].

In a large number of underground coal mines, at the present time, the schemes for the preparation of the seams are operated by coupled workings, leaving the non-recoverable pillars, which provide a fairly high efficiency and safety of operation in the coal mine [48].

Methane explosion can occur at a volume concentration of 5–15% in a mixture with air, and it is almost 2 times lighter than air. Methane is dangerous because even at high concentrations, coal mine workers cannot detect it on their own, because methane is characterized by an absence of smell and color. Various ventilation systems and gas monitoring systems are used to dilute the methane jet stream in the coal mine to minimum concentrations and safe mining operations [49,50].

It is also known that combustible coal dust is an explosive aerosol, so coal dust increases the explosive properties of methane. Powdered coal or coal dust causes various respiratory diseases, which is a serious occupational hazard. Coal dust is generated by the impact of the drums of a shearer during coal mining, loading, transport of coal and drilling.

Methane explosions have a more negative impact on the material condition of the enterprise, leading to the loss of coal and injuries of miners. Explosions also cause huge emissions of gas and dust in the Earth's atmosphere. The products isolated due to methane explosions were transported significant distances by wind, so air pollution was added to all the consequences. As a result of coal combustion, the resulting substances are discharged into reservoirs that are placed on the surface, thus polluting the water of the Earth [51–53]. That is why early prediction and prevention of methane–air mixtures is important to reduce the impact of coal mines on the Earth's atmosphere.

Typically, an underground explosion causes a fire and, conversely, an endogenous fire can ignite and detonate methane. In order to predict the possible explosion of a mixture of methane and air in a coal mine, technological mining development systems and bed ventilation systems are put into operation [54,55]. Drainage systems are also used to drain excavated areas and to ensure reliable insulation of waste areas. In order to prevent fires and methane explosions prematurely, it is necessary to operate electrical equipment in an explosion-safe mode, not to allow open fire and sparks, to minimize drilling and blasting operations and to produce all requirements of dust and gas operation of the mine [56–58].

To prevent coal mine dust from igniting, the use of irrigation systems, water curtains, as well as rational vent schemes for local workings is required [59,60].

Gas monitoring systems have been used in modern coal mines since the late 20th century. At the same time, enterprises operate different types of information technology-based systems to control the level of methane in coal mines [61–63]. Different types of sensors are used to analyze mine atmosphere. Table 3 summarizes the sensors used to measure the indicators, as well as the MAC (maximum allowable concentration) for each indicator [64,65].

Table 3. Basic sensor parameters.

Name	Sensor	MAC (g/m^3)	MAC (ppm)
MQ-2	Methane	0.5%	500
MQ-4	Methane	0.5%	500
MQ-7	Carbon dioxide	0.0017%	1.7
MQ-9	Propane	2.2%	2200
MQ-135	Carbonic gas	2%	2000

Methane monitoring sensors are installed at various locations in the mine, such as a longwall face, roads and ventilation workings, etc. Air sensors are installed in the same place as the methane sensors and additionally in the main ventilation fan shafts. If the gas concentration threshold is exceeded, the power supply is cut off [66–68].

The materials presented in Table 4 were used to create the simulation model.

Table 4. Materials for the simulation model.

Materials	Number of Units
Arduino UNO board	1
MQ-4 sensor	1
LED	2
Buzzer	1
Resistor 3 220 Ohm	3
Jumper wires	6
Methane concentration determination	1

The main task is to develop a software and hardware complex for monitoring methane in underground coal mines by creating a simulation model for monitoring methane in domestic conditions with the help of the Arduino Uno board and the methane sensor MQ-4 [69–71]. The specifications of the MQ-4 sensor are presented in Table 5.

Table 5. Specifications of the MQ-4 sensor.

Device Characteristic	Value
Detecting concentration	300 to 10,000 ppm
Power	150 mA
Input voltage	5 VDC
Digital output voltage	TTL digital 0 and 1 (0.1 V and 5 V)
Analog output voltage (relatively clean)	0.1 V to 0.3 V
Analog output voltage (highest concentration)	4 V

3. Results

Mathematical model. The input value for modeling an optoelectronic sensor is the measured gas level, which is the integral transmittance of the gas cell's optical radiation [24,72,73].

The block diagram of an optoelectronic sensor for measuring methane is shown in Figure 2.

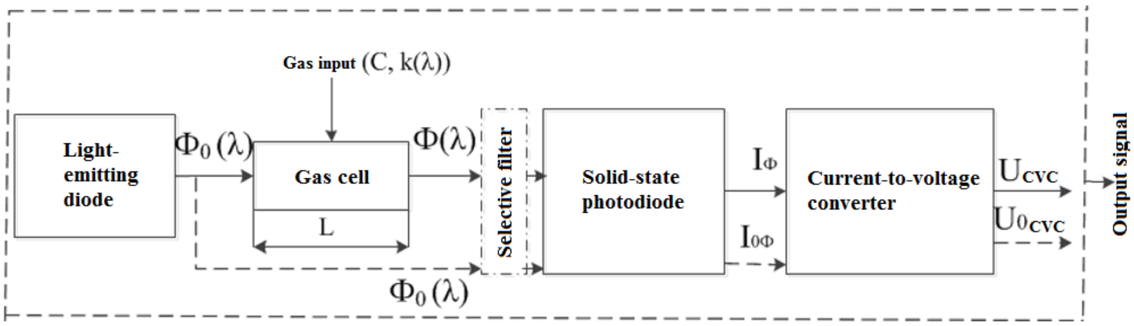

Figure 2. Structural scheme of the EOS. Source: Compiled by the author.

The EOS (electro-optical system) and a photodiode are source for measuring the concentration of methane by a simulated sensor, which in turn is a radiation receiver.

Light and photodiodes are located on the same optical axis. The exit and entrance pupils of both the light and the photodiode are respectively directed to each other. To reduce sensitivity to other gases present, the EOS has the ability to activate a light filter [74,75].

An approach to modeling the EOS of measuring gas concentration consists in calculating the spectral transmittance using the Bouguer–Lambert–Beer law, based on data on the spectral absorption coefficient of a gas mixture [5]:

$$\tau(\lambda) = \frac{\Phi(\lambda)}{\Phi_0(\lambda)} = e^{-k(\lambda)LC}, \quad (1)$$

where $\Phi_0(\lambda)$—spectral flux of probing radiation, W; $\Phi(\lambda)$ is the spectral flux of radiation (W) passing through a gas with concentration C (in volume fraction), spectral absorption coefficient of the gas mixture $k(\lambda)(m^{-1})$ with an absorption path length L(m).

The following dependence determines the transfer function of the sensor [6]:

$$\tau(C) = \frac{\int_{\lambda 1}^{\lambda 2} S_i(\lambda)\cdot\Phi_0(\lambda)\cdot\tau_{cf}(\lambda)\cdot e^{-k(\lambda)LC}\cdot\prod_1^N e^{-k_i(\lambda)LC_i}d\lambda}{\int_{\lambda 1}^{\lambda 2} S_i(\lambda)\cdot\Phi_0(\lambda)\cdot\tau_{cf}(\lambda)d\lambda}, \quad (2)$$

where $S_i(\lambda)$ is the spectral sensitivity of the photodetector (photodiode), A/W; $\Phi_0(\lambda)$ is the spectral flux of the probing radiation of the source (EOS), W; τ_{cf} (λ) is the spectral transmittance of the light filter; $k(\lambda)$—spectral absorption coefficient of the studied gas, m^{-1}, L—length of the absorbing gas layer, m; C is the concentration of the studied gas; $k_i(\lambda)$—spectral absorption coefficient of the i-th foreign gas, m^{-1}; C_i is the concentration of the i-th foreign gas [76–78].

Based on the transfer function of the EOS of the gas concentration, the sensitivity, the absolute and relative error in measuring the gas concentration, and the detection threshold are estimated.

The sensitivity of the sensor is determined by the slope of the transfer characteristic $S(C) = \frac{\partial\tau}{\partial C}$. From this ratio, the sensitivity value $\Delta C = \frac{\Delta\tau}{S(C)}$ is determined.

For a given sensor signal–noise ratio μ, the minimum recorded change $\partial\tau$ is $1/\mu$, and the absolute measurement error and detection threshold are calculated based on the following dependencies [79,80]:

$$\Delta C = \frac{1}{\mu\cdot S(C)}, \quad (3)$$

$$LOD = \frac{1}{\mu\cdot S(C \to 0)}, \quad (4)$$

The value of the relative error of the result obtained is defined as—$\delta = \Delta C/C$.

Information about the spectral flux emanating from the radiation source, the sensitivity of the photodetector, the absorption coefficient of methane and the calculation of the signal–noise ratio is needed in order to calculate the transfer function value and the measurement deviation of the optoelectronic methane measurement sensor.

The value of the main gas mixture composition's presence is established, including the replacement of the emitted gases O_2 and N_2 in the atmosphere during the process of modeling the sensor for determining the level of concentration of the main gases [79–81].

The decrease in the concentration of oxygen in the mine atmosphere due to methane emissions is calculated using the following ratio:

$$C_{O_2} = 0.21(1 - C_{CH_4}), \quad (5)$$

and the decrease in nitrogen according to this formula:

$$C_{N_2} = 0.70(1 - C_{CH_4}), \quad (6)$$

The signal–noise ratio at the output of the CTC of the simulated sensor is calculated by the formula:

$$\mu = \frac{U_{cvc}}{U_{sh}} \quad (7)$$

where U_{cvc} is the useful signal at the CVC output when the input of the photodiode is exposed to radiation from the source (in the absence of an absorbing medium), V; U_{sh}—root-mean-square value of the noise at the CVC output, V.

The CVC output signal can be calculated based on the formula:

$$U_{cvc} = K_{cvc} \cdot (I_d + I_f), \tag{8}$$

where I_d is the dark current of the photodiode, A; I_f—photocurrent due to external radiation, A; K_{cvc}—CVC conversion factor, V/A.

The photocurrent generated by the EOS photodiodes is calculated by the formula:

$$I_\Phi = k_{eoc} \cdot k_L \cdot \int_{\lambda 1}^{\lambda 2} S_I(\lambda) \cdot F_{e0}(\lambda) \Delta\lambda, \tag{9}$$

where λ_1, λ_2 is the spectral range in which radiation is received by the photodiode; $S_I(\lambda)$ is the spectral current sensitivity of the photodetector, A/W; $F_{e0}(\lambda)$—spectral radiation flux from the EOS, W; k_{eos} = 0.1—coefficient of efficiency of the optical system; k_L is the coefficient that determines the dependence of the photocurrent on the distance l between the EOS and the photodiode (from 0 to 1) [82,83].

From the data given in the technical documentation for optocouplers (EOS-photodiode, we know the coefficient k_L) (Figure 3) [84–86].

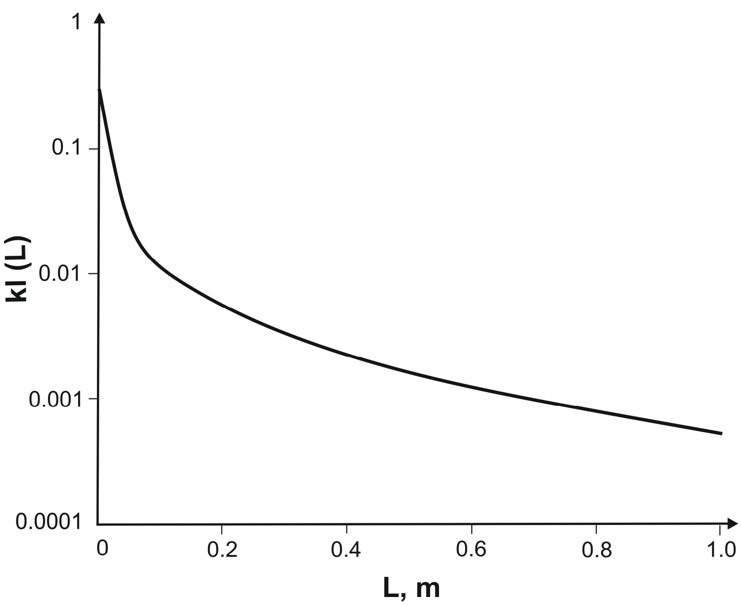

Figure 3. Coefficient definition k_L.

RMS value of the noise at the CVC output Us is described by the expression:

$$U_s = \sqrt{\left\{ (U_y^*)^2 \left[\left(1 + \frac{R_{OC}}{R}\right)^2 + \frac{4\pi^2}{3} (\Delta f)^2 C_e^2 R_{OC}^2 \right] + R_{OC}^2 (I_e^*)^2 + 4kTR_{oc} \right\} \cdot \Delta f}, \tag{10}$$

where $(U_y^*)^2$ is the noise spectral density by voltage OA, V^2/Hz; R—equivalent resistance, Ω; R_{oc} is the resistance of feedback, Ω; C_e is the equivalent capacitance, F; $(I_e^*)^2$ is the total noise current spectral density A^2/Hz; k is the Boltzmann's constant, $1.38064852 \times 10^{-23}$, $J \cdot K^{-1}$; T is the photodiode temperature, K; Δf is the bandwidth of the circuit, Hz.

Figures 4–6 present research data for sensors of carbon monoxide, carbon dioxide and methane.

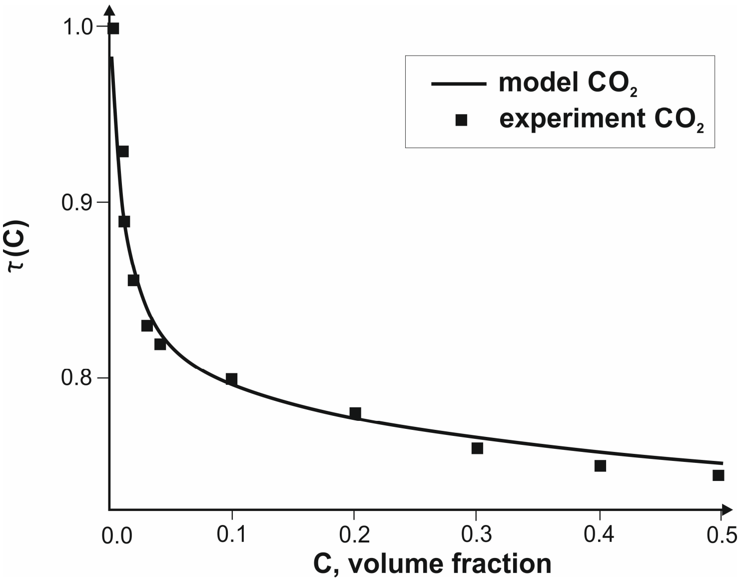

Figure 4. Transfer functions for the CO_2 sensors.

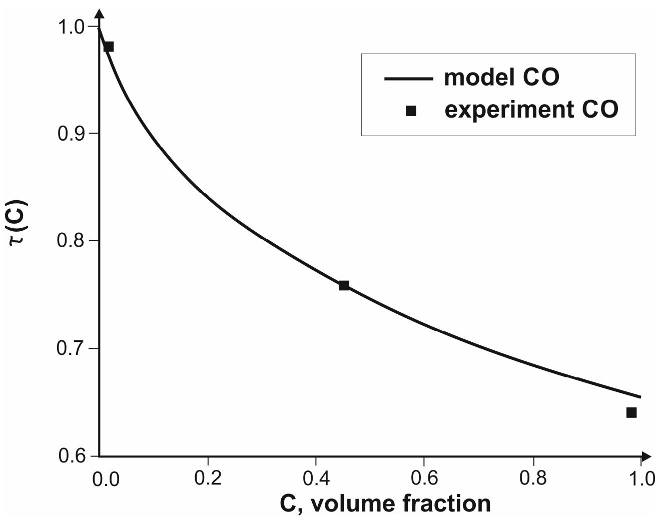

Figure 5. Transfer functions for the CO sensors.

The data obtained as a result of experimental studies on the transfer functions for sensors of carbon monoxide, carbon dioxide and methane are consistent with the results of the simulation [85,86]. The relative error of modeling the carbon dioxide sensor is less than 5%, carbon monoxide is less than 5% and methane is less than 4%.

A comparative analysis of the calculated values of the signal–noise ratio with experimental data was also carried out.

Thus, based on the significant agreement between the results of modeling the transfer functions and the signal–noise ratio with experimental data, the adequacy of the computer model is confirmed [87,88].

The development of hardware and software systems. To create a simulation model for determining the concentration of methane in the atmosphere, an Arduino UNO board, an analog MQ-4 methane concentration determination sensor, 2 LEDs, a buzzer, 3 220 Ohm resistors, 6 jumper wires and methane concentration determination tool were used. To develop the code for the program for determining the concentration of methane, the Arduino IDE development environment was used.

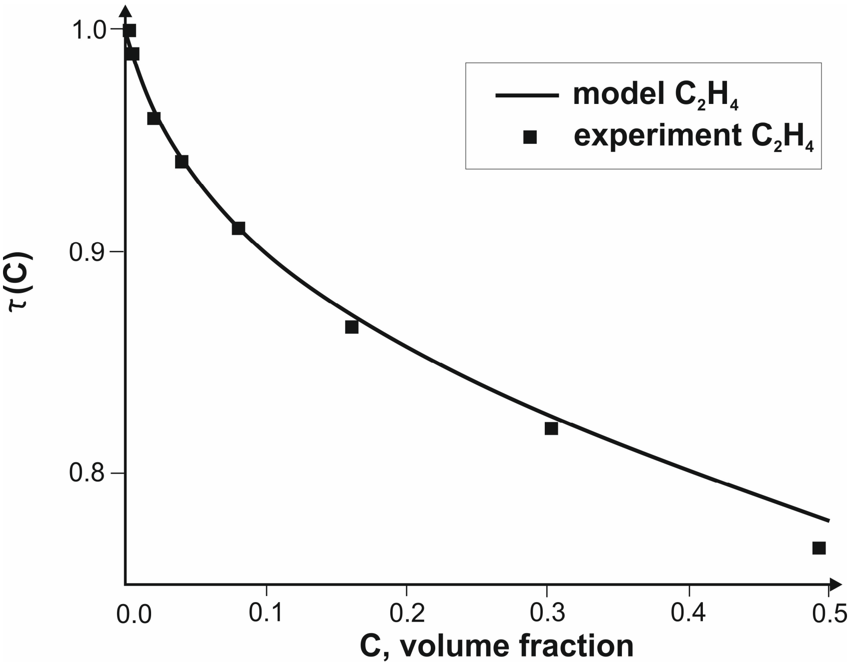

Figure 6. Transfer functions for the C_2H_4 sensors.

The scheme of the model is shown in Figure 7.

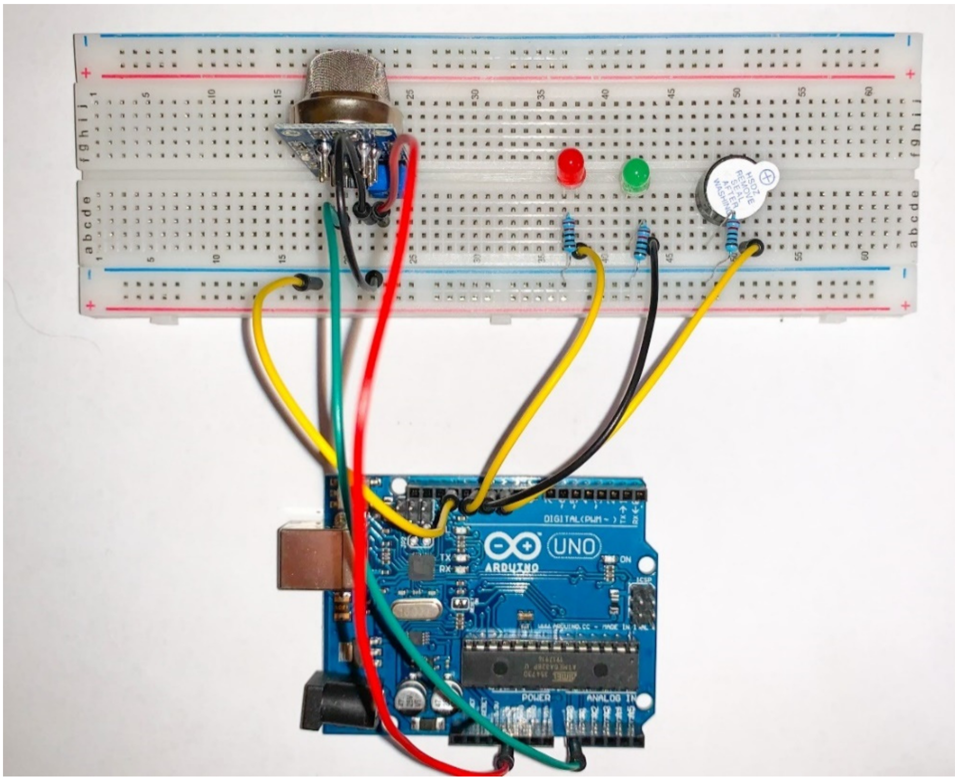

Figure 7. The scheme of the model. Source: Compiled by the author.

In the Arduino IDE development environment, the program code for the functioning of the methane monitoring installation was written. The program code looks like this:

```
#define MQ4pin (0)
#define redLed (12)
#define greenLed (11)
#define buzzer (10)
float sensorValue;
void setup()
{
  Serial.begin (9600);
  Serial.println("Gas sensor warming up!");
  Delay (20,000);
}
void loop()
{
  sensorValue = analogRead (MQ4pin);
  if (sensorValue > 300)
  {
    Serial.print ("Methan: ");
    Serial.print (sensorValue);
    Serial.println (" | Exceedance concenration!");
    digitalWrite (redLed, HIGH);
    digitalWrite (greenLed, LOW);
    tone (buzzer, 1000, 200);
  }
  else
  {
    Serial.print ("Methan: ");
    Serial.println (sensorValue);
    digitalWrite (redLed, LOW);
    digitalWrite (greenLed, HIGH);
    noTone (buzzer);
      }
  Delay (2000);
}
```

1. At first, we determine the analog numbers of the Arduino pin to which the MQ-4 methane sensor, red and green LEDs, and the buzzer module are connected. SensorValue—variable for storing MQ-4 sensor values.

```
#define MQ4pin (0)
#define redLed (12)
#define greenLed (11)
#define buzzer (10)
float sensorValue;
```

In the setup () function, we activate serial communication with the PC and wait 20 s to warm up the sensor.

```
void setup () {
  Serial.begin (9600);
  Serial.println ("Gas sensor warming up!");
  Delay (20,000);
}
```

2. The serial port monitor when the sensor warms up looks like this (Figure 8):

3. In the loop () function, using the analogRead () function, we read the sensor value and write it to the sensorValue variable.

```
void loop () {
    sensorValue = analogRead (MQ4pin);
```

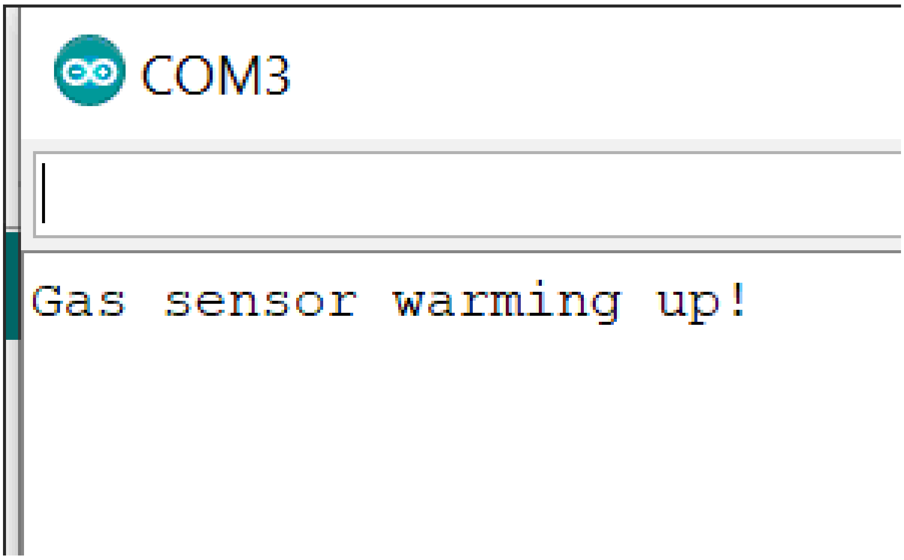

Figure 8. Serial port monitor when the sensor heats up MQ-4. Source: Compiled by the author.

4. Next, check the sensor value for exceeding the concentration threshold. When the concentration is high enough, the sensor detects a value above 300. To track the excess concentration, the "if" statement can be used. If the sensor reading exceeds 300, then in the serial port monitor we display the sensor value with the message "Ex-ceedance concentration!", the red LED lights up and the buzzer sounds. If the sensor reading is below the concentration limit, then the green LED is on and only the sensor value is displayed on the serial port monitor (Figures 9 and 10). Due to the fact that it is impossible to create real conditions in a coal mine in domestic conditions, the concentration of methane in the atmosphere is very low, so it is necessary to use a third-party source of methane, the methane concentration determination tool in this case. When gas is opened near the sensor, an increase in methane is observed.

```
if(sensorValue > 300)
  {
    Serial.print ("Methan: ");
    Serial.print (sensorValue);
    Serial.println (" | Exceedance concentration!");
    digitalWrite (redLed, HIGH);
    digitalWrite (greenLed, LOW);
    tone (buzzer, 1000, 200);
  }
  else
  {
    Serial.print ("Methan: ");
    Serial.println (sensorValue);
    digitalWrite (redLed, LOW);
    digitalWrite (greenLed, HIGH);
    noTone (buzzer);
      }
```

The value of the sensor shown on the Figure 11 and the results of its functioning, which are shown on the Figure 12 approved the fact that the alarm activation when the methane concentration reaches 300 mol/dm is working correctly.

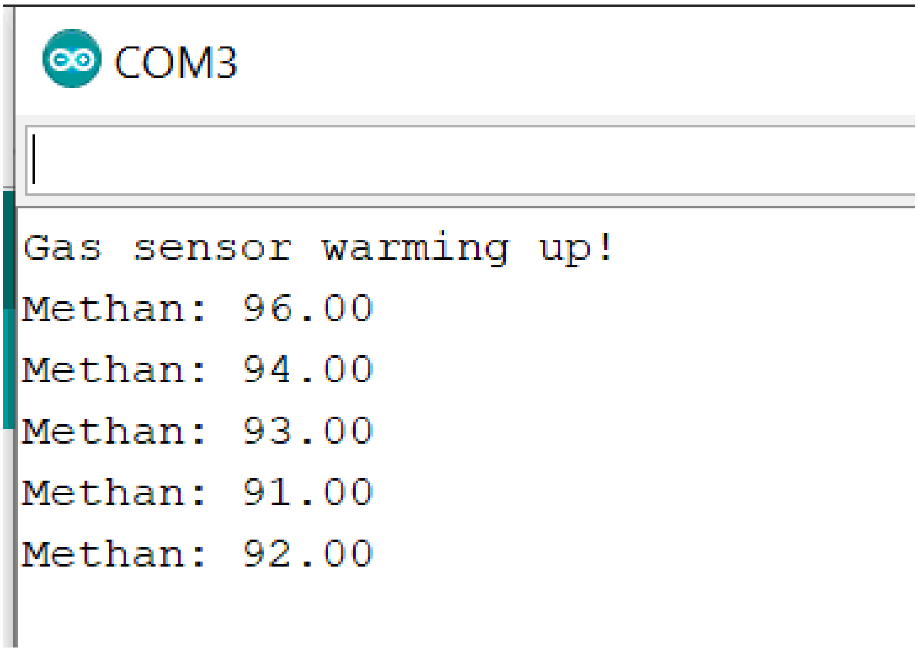

Figure 9. Serial port monitor until the methane threshold sensor values are reached.

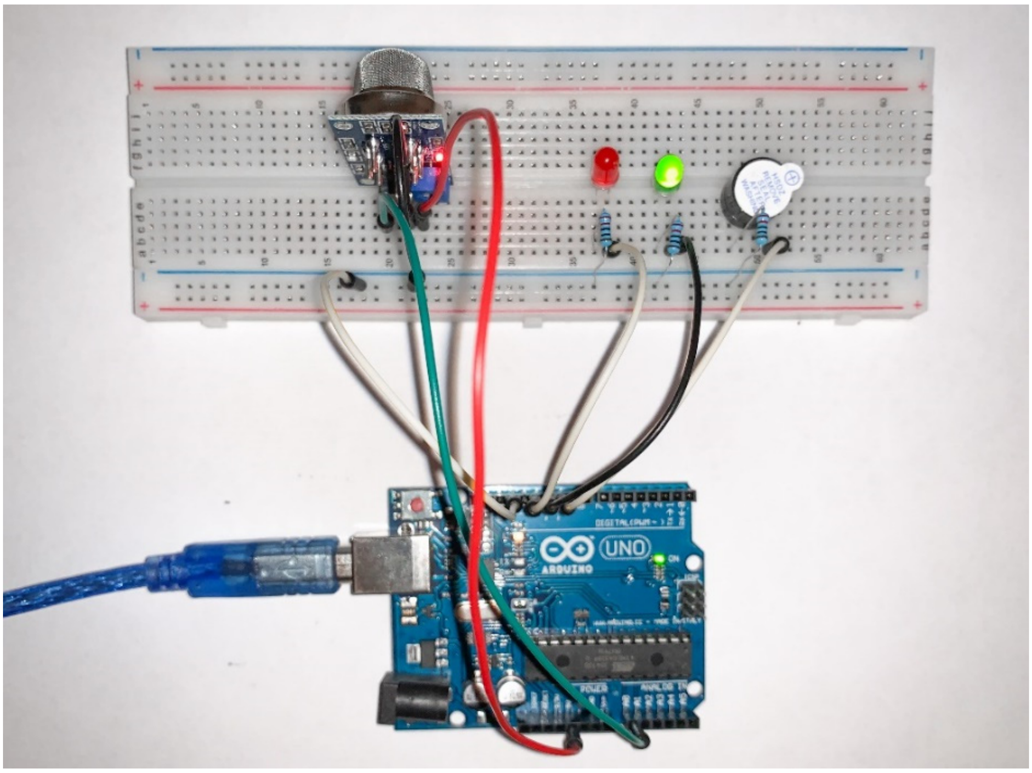

Figure 10. Diagram of the model at a normal value of methane concentration; the green LED lights up. Source: Compiled by the author.

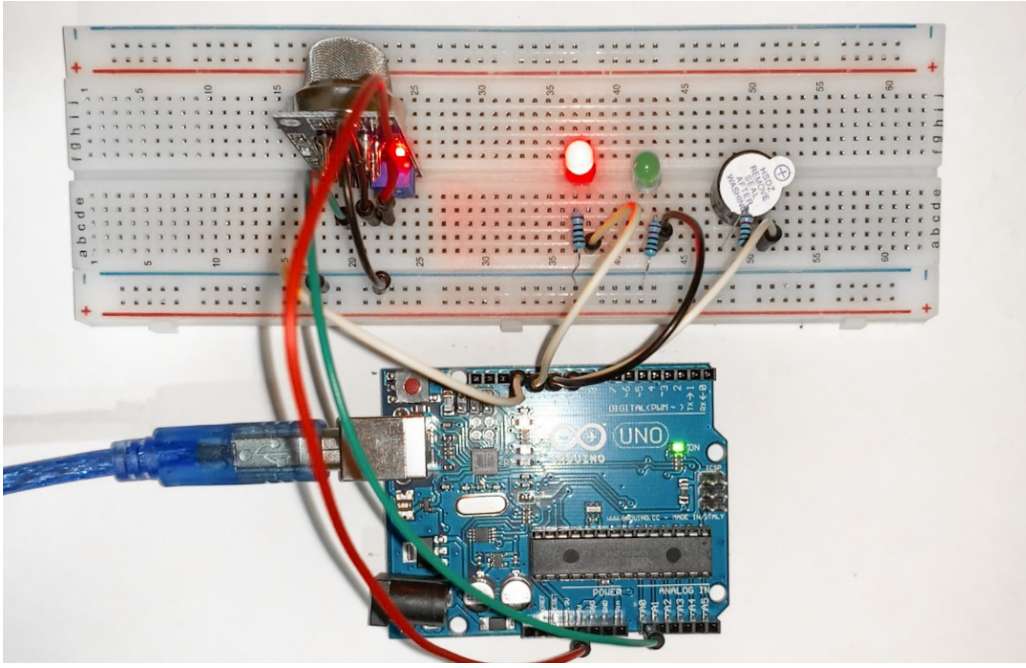

Figure 11. Scheme of the model when the threshold value of methane concentration is exceeded by the MQ-4 sensor; the red LED lights up. Source: Compiled by the author.

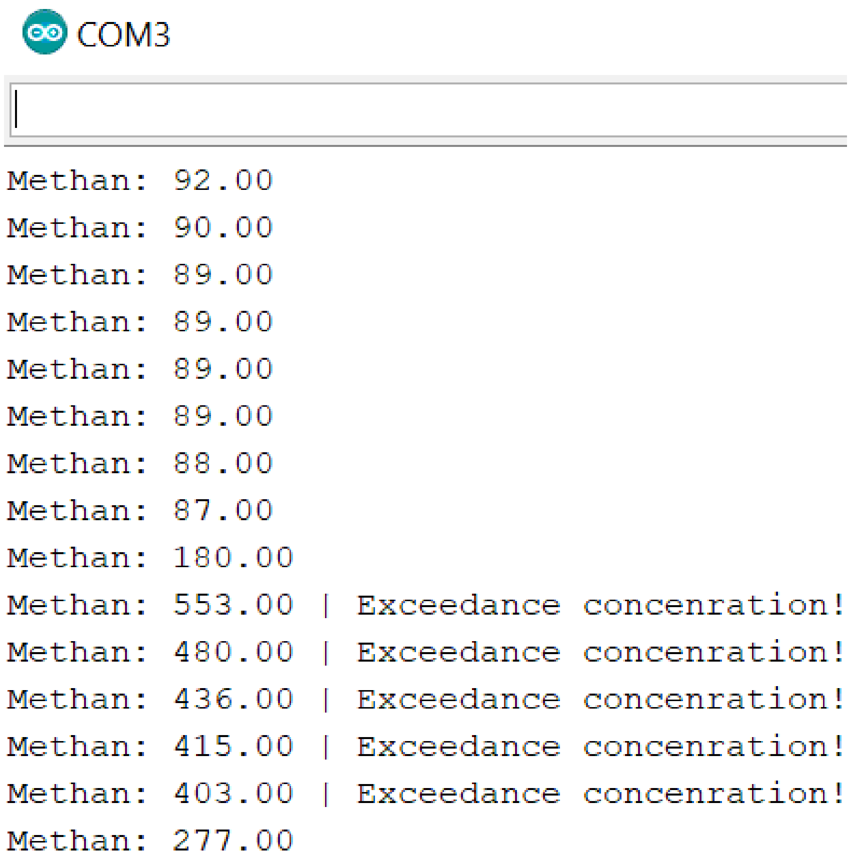

Figure 12. Serial port monitor when the sensor exceeds the threshold concentration of methane MQ-4.

The pause between the display of sensor readings is 2 s.

```
 Delay (2000);
}
```

As a result of the work, a simulation model for monitoring the methane concentration was developed. The values of the sensor, which measures the level of methane in the atmosphere, are displayed in the monitor of the serial port. When the methane level is normal, the green LED lights up; when the concentration limit, which is 300 ppm, is exceeded, the red LED lights up, the buzzer emits a signal and in the serial monitor. In addition to the methane concentration value, the message about exceeding the limit value is displayed—"Exceedance concentration! (Excess concentration!)".

A hardware–software complex for methane monitoring has been developed using the Arduino Uno platform and the MQ-4 methane level sensor. The developed complex can improve the safety of the works in the coalmines.

The accumulated amount of knowledge and systems for monitoring methane concentrations can be used to ensure the safety of the coal gas-bearing seams exploitation process, as well as for the possible scientific research in this subject area.

It should be noted that, as a result of the work, a patent for the invention "Method for developing a thick flat layer of mineral resources" was issued [89]. Also, the license of the computer program "Assessment of the economic efficiency of using the oil separator in the Arctic zone" registration, using the Arduino platform, was received [90].

Analysis of the literature on the research subject revealed that there are several full-featured products capable of monitoring gas concentration [91–93]. The advantages of such developments are a large number of monitoring functions. But the problem is the complexity of implementation of such systems. These systems have a high cost [94–101]. The use of monitoring systems implies changes in every step of the production process. As a result of this work, a prototype including using the Arduino Uno platform and the MQ-4 methane level measurement sensor was created and tested.

Data collection and construction of the predictive model. Data on methane concentration in a coal mine is collected using special gas analyzers that measure the methane content in the air. Hard coal is used as a source of gas. The following algorithm of data collection on the simulator is used:

1. Equipment Setup: Ensure that the analyzer is in good working order and calibrated according to the manufacturer's specifications. Also make sure that the sensors and probes are clean and ready for use.
2. Safety: All necessary precautions should be taken and safety rules observed before beginning data collection, as methane is a highly explosive gas.
3. Positioning the gas analyzer: The gas analyzer should be placed at the desired point in the mine where the methane concentration is to be measured. This is usually the location where dangerous methane concentrations are most likely to occur.
4. Measurement: After installing the gas analyzer, it is necessary to wait for the readings to stabilize. The gas analyzer can then be used to obtain continuous or periodic measurements of the methane concentration in the mine.
5. Data recording: Methane concentration data obtained should be recorded with the time and location of the measurements. This allows tracking changes in methane concentration in different parts of the mine and analyzing potential hazards.

By performing the above algorithm, the methane concentration data were obtained. The obtained data are presented in Table 6.

The results have shown that the developed hardware–software system will allow us to identify the methane distribution in space. Let us build a predictive model of methane movement and its concentration. To build this model we will use the methods of system analysis presented in [102–107]. By conducting a number of experiments and comparing all the data as shown in [108,109], a logarithmic dependence of the methane content was obtained. Thus, the correctness of the developed device is confirmed.

Table 6. Data obtained experimentally.

Time	Sensor Number										
	1	2	3	4	5	6	7	8	9	10	11
10	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
30	0.1	0	0	0	0	0	0	0	0	0	0
40	0.1	0.1	0	0	0	0	0	0	0	0	0
50	0.1	0.1	0	0	0	0	0	0	0	0	0
60	0.3	0.1	0.1	0	0	0	0	0	0	0	0
70	0.3	0.1	0.1	0	0	0	0	0	0	0	0
80	0.3	0.3	0.1	0.1	0	0	0	0	0	0	0
90	0.3	0.3	0.1	0.1	0	0	0	0	0	0	0
100	0.3	0.3	0.3	0.1	0.1	0	0	0	0	0	0
110	0.3	0.3	0.3	0.1	0.1	0	0	0	0	0	0
120	0.3	0.3	0.3	0.3	0.1	0.1	0	0	0	0	0
130	0.3	0.3	0.3	0.3	0.1	0.1	0	0	0	0	0
140	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0	0	0	0
150	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0	0	0	0
160	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0	0	0
170	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0	0	0
180	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0	0
190	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0	0
200	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0

4. Discussion

One of the most important problems in coal mines is the presence of sources of methane; a dangerous gas that can pose a serious threat to the lives and health of miners. Methane, although a mineral also known as natural gas, is highly flammable and can cause explosions and fires in mines. Therefore, methane monitoring in coal mines is critical to ensure worker safety and prevent catastrophic accidents. Highlighting the key aspects of the importance of methane monitoring, we would like to note the following.

First, methane monitoring helps us to detect the concentration of gas in the air in a timely manner. If the concentration exceeds safe limits, it can lead to a fire or explosion. When using modern monitoring systems, even small changes in methane levels can be automatically detected, which allows taking prompt action to prevent emergencies and evacuate employees.

Second, methane monitoring is a key aspect of a coal mine prevention and safety plan. Regular measurements of methane concentrations can identify high hazard areas and take the necessary steps to prevent methane buildup. For example, if high methane levels are detected in a particular area, additional ventilation can be implemented, barriers can be created to prevent the gas from spreading, or work in the area can be temporarily suspended until the situation normalizes.

Third, methane monitoring allows the mine administration to evaluate the effectiveness of the ventilation system and other safety measures. By installing methane sensors in different areas of the mine, the data can be analyzed to determine where additional attention and enhanced safety measures are needed.

However, methane monitoring requires not only the installation of appropriate sensors in mines, but also the training of personnel, as well as the development and implementation of strict protocols and regular inspection of monitoring systems. To reduce the importance of the human factor in recording gas concentrations, it is advisable to use automated systems for collection, storage and decision support. Within the framework of this study a hardware–software complex was developed, which allows gas monitoring without human participation [110–112]. Thus, the presence of human factors is minimized. The key feature of the developed complex is the possibility of diagnostics of gas advancement along the mine shaft. As practice has shown, such possibility will allow us to use the ventilation system more rationally. We would like to note that in a number of cases forced ventilation of the mine was carried out in the wrong direction, toward people. The developed complex allows predicting the movement of methane cloud and controlling its movement.

In the literature, there are quite a lot of works in this area, but the presented work is favorably distinguished by the extension of the functionality of monitoring systems [113–116]. Thus, the presented work can be useful for both specialists in the field of information technology and the organization of mining production.

5. Conclusions

Effective management of coal seam methane, based on monitoring of methane concentrations, creates conditions not only to reduce the risk of methane explosions, but also to improve the efficiency of methane recovery and utilization and minimize methane emissions to the atmosphere. Therefore, continuous efficient monitoring of methane is key to ensuring sustainable underground mining of gas-bearing coal seams.

As a result of this work, research has been conducted on methane monitoring systems in coal mines. Characteristics and structure and technological process of systems for monitoring the atmosphere of coal mines, causes of risks and accidents at coal mines have been studied. Methane detection and prevention systems, existing methane monitoring systems and underground coal mine methane utilization methods, characteristics of different sensors for mine atmosphere detection has been analyzed. The numerical results of the research are presented by the graphs.

A software and hardware system for monitoring methane in coal mines has been developed using the Arduino Uno platform and the MQ-4 methane level measurement sensor. Using a methane monitoring system in coal mines would make it possible to ensure the efficient and safe mining of gas-bearing coal seams using high-performance longwalls.

The presented research is one step toward full-featured control and monitoring system development. Future research will be related to the involve validation of a full-featured monitoring system in the active underground mines.

6. Patents

Sirenko Yu.G., Sidorenko S.A., Denisova A.I., Mironovich M.P. Invention Patent № 2760450, publication date 21 November 2021, request № 2021115475/03 (31 May 2021), «Method for developing a thick flat layer of mineral resources».

Author Contributions: Conceptualization, S.S.; methodology, S.S.; software, V.T.; validation, V.T.; formal analysis, V.T.; investigation, V.T.; resources, A.S.; data curation, A.S.; writing—original draft preparation, S.S.; writing—review and editing, S.S.; supervision, V.T.; project administration, S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Sidorenko A.A. was employed by the company JCS SUEK. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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