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Variability of CO_2, CH_4, and O_2 Concentration in the Vicinity of a Closed Mining Shaft in the Light of Extreme Weather Events—Numerical Simulations

Paweł Wrona [1,*], Zenon Różański [1], Grzegorz Pach [1], Adam P. Niewiadomski [1], Małgorzata Markowska [2], Andrzej Chmiela [3] and Patrick J. Foster [4]

1 Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, Akademicka 2, 44-100 Gliwice, Poland; zenon.rozanski@polsl.pl (Z.R.); grzegorz.pach@polsl.pl (G.P.); adam.niewiadomski@polsl.pl (A.P.N.)
2 Główny Instytut Górnictwa, Państwowy Instytut Badawczy (Central Mining Institute, National Research Institute), Plac Gwarków 1, 40-166 Katowice, Poland; mmarkowska@gig.eu
3 Spółka Restrukturyzacji Kopalń, ul. Strzelców Bytomskich 207, 41-914 Bytom, Poland; achmiela@srk.com.pl
4 Camborne School of Mines, University of Exeter, Penryn TR10 9FE, UK; p.j.foster@exeter.ac.uk
* Correspondence: pawel.wrona@polsl.pl

Abstract: With climate change, more intense weather phenomena can be expected, including pressure drops related to the arrival of an atmospheric front. Such drops of pressure are the main reason for gas emissions from closed mines to the surface, and a closed, empty mine shaft is the most likely route of this emission. Among the gases emitted, the most important are carbon dioxide and methane, creating a twofold problem—greenhouse gas emissions and gas hazards. The work presented in this paper simulated the spread of the mentioned gases near such an abandoned shaft for four variants: model validation, the most dangerous situations found during measurements with or without wind, and a forecast variant for a possible future pressure drop. It was found that a momentary CO_2 emission of 0.69 m^3/s and a momentary CH_4 emission of 0.29 m^3/s are possible, which for one hour of the appropriate drop would give hypothetically 2484 m^3 CO_2 and 1044 m^3 CH_4. In terms of gas hazards, the area that should be monitored and protected may exceed 25 m from a closed shaft in the absence of wind influence. The wind spreads the emitted gases to distances exceeding 50 m but dilutes them significantly.

Keywords: greenhouse gas; CFD; gas hazard; climate change; post mining

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1. Introduction

Climate change can lead to increasingly severe or prolonged weather events [1]. These phenomena may have a negative impact on the structure of a closed mine, causing a threat to the environment and the local population. In the long-term perspective, safety should be a priority during the closure of mines and the transformation of post-industrial areas. The predicted phenomena caused by weather anomalies include a number of issues such as: increased erosion and destabilization of slopes on post-mining landfills and mining subsidence [2,3], increased migration of pollutants through these landfills and their flow to the ground or the surrounding watercourses or water reservoirs [4], as well as increased gas emissions [5].

The phenomenon of gas emissions from closed mines is known because such emissions have been recorded in many significant mining basins around the world.

The most important of the emitted gases are greenhouse gases, i.e., carbon dioxide and methane [6]. An abandoned shaft is the most probable path of gas emissions [7,8].

Currently, scientific work on the phenomenon of gas emission from the rock mass is carried out in the following directions. Sechman, along with other authors [9], determined the origin and concentrations of methane and carbon dioxide concentrations in a part of The Upper Silesian Coal Basin.

Duda and Krzemień [10] presented a forecast of methane emissions conducted within the framework of the Research Fund for Coal and Steel project "MERIDA". They estimated the volume of methane emitted into longwall goafs from relaxed undermined and overmined coal seams. It led to an assessment of the risk of methane emissions into the atmosphere from abandoned coal mines. Duda and Valverde [11] also elaborated on a risk analysis of the methane hazard at the final stage of the closure process of a Polish mine. It is also a major topic in the article by Valverde et al. [12].

Aspects of gas emissions affected by flooding were investigated by Krause and Pokryszka [13]. Lunarzewski in the paper [14] investigated the variation of methane emissions after longwall closure. Methane emissions from closed mines were also investigated by Dreger [15] and Kędzior [16].

The analysis of the gas emissions mechanism is also a current research direction. So far, it has been established that the main force causing the emission of gases to the surface is the decrease in atmospheric pressure. In the case of the researched topic, the occurrence of increasingly strong weather phenomena may be associated with more intensive drops and thus with increased emission of gases from underground excavations. It is stated that climate change may be a reason for more intense and frequent weather events like severe storms [17,18] (when pressure drop intensity could reach 5 hPa/h).

These predictions are the basis for the hypothesis that, in the future, more intense pressure drops may cause a greater threat associated with the emissions of gases from the rock mass. The most probable routes of gas emission are decommissioned shafts which can be found in post-mining areas. The level of fill in the shaft is important as the lack of backfilling material in a shaft will give rise to emissions of mine gases to the atmosphere as well as in terms of safety in the vicinity of the shaft.

For instance, in the northeastern part of Upper Silesia, there are 685 old mining excavations [19], of which 24 are left for water pumping purposes. However, the problem is not only local to Polish mines, rather, it is related to every coal mining basin in the world [5].

The status of many shafts is largely unknown in terms of security and backfilling [20]. The level and material type of filling up the shaft are also important. Lack of charging in the shaft is an unfavorable situation in terms of the emission of mine gases into the atmosphere as well as in terms of safety in the vicinity of the shaft. In the GZW area, gases can flow through them hydraulically [21].

Therefore, the TEXMIN project [1], carried out for 3.5 years between 2019 and 2022, focused, among other things, on examining the range of gas emissions from abandoned mine shafts and, at the same time, estimating the volume of the expected emissions along with the expected more numerous or intensive pressure drops that may be associated with so-called extreme weather events. These studies fill the gap between the previously referenced work and the present problems of maintaining the mining shaft of a closed mine in or around public or private terrain. The factor determining whether the shaft should be left empty may be the need to maintain the lowered water level after the end of exploitation by pumping groundwater. In doing this, one should also take into account the risk of a sudden fall of the backfill material [6], but such events should be treated as a rare occurrence.

The research carried out during the TEXMIN project and presented In this paper is also important when using underground post-mining voids for other tasks, e.g., CCS technology, energy storage in compressed air [22–24], and other activities connected with the topic [25].

The paper presents the results of CFD simulations of gas emissions and the distribution of carbon dioxide, methane, and oxygen concentrations around the Gliwice II shaft, which was left empty for the purpose of water pumping. Taking into account the expected intensification of weather phenomena, their abruptness, and the related occurrence of deeper pressure drops, various variants of pressure drops were taken into account during the simulation, with variable wind speed set values. The research carried out was the next step and extension in relation to previous research [26]. The novelty is presented below.

In the article [5], measurements were presented from the years 2013 to 2016 for the site. These results were the basis for developing the first numerical model of the studied phenomenon. This numerical model was presented in the article [6]. This original model was simplified, without any obstacles, the mesh density was less accurate, the cell size was 0.62 m, and the concentration of both gases was set at 5.0 vol %. The rate of emissions was determined based on the equations given in the article [5]. Next, the research was focused strictly on emissions simulations without testing the distribution of gases around the shaft, using Ansys Fluent v.16 as a tool. The phenomenon of outflow inertia was also investigated, and it was proven that emission can also take place in the initial phase of pressure increase following an intense barometric drop [27]. As the next step, just after the TEXMIN project started and after completing measurements, preliminary results were presented in the article [26].

The current paper provides a new, more detailed numerical model corresponding to the situation in the field. A denser measurement grid was applied, and simulations were related to the actual measuring results and projections of weather. Oxygen variations were also taken into account in the tests for the first time.

Additionally, during many years of work on the issue, the authors have come across many studies on the issue, but no one has previously conducted such detailed simulations of gas emissions from a closed shaft. They are focused on the value of emission intensity, its changes resulting from changes in atmospheric pressure, as well as the maximum values of concentrations of emitted gases, i.e., in [9]. The literature also contains research results on greenhouse gas emissions (mainly methane) from the area of mining and post-mining in general [28,29].

2. Methods

2.1. The Site

The studies took place on an abandoned shaft, Gliwice II (which closed in 2000), belonging currently to SRK (in Polish: Spółka Restrukturyzacji Kopalń). The overview of the site is presented in Figures 1 and 2. As it was noticed in Section 1, the shaft was left empty for water pumping purposes. The depth of the shaft is 553.2 m. The neighboring operating "Sośnica" coal mine requires the "Gliwice II" shaft for water pumping purposes. The shaft is connected with three coal seams.

Figure 1. Overview of the site. The point of emissions is visible in the center of the frame. A shed is on the right side (own picture).

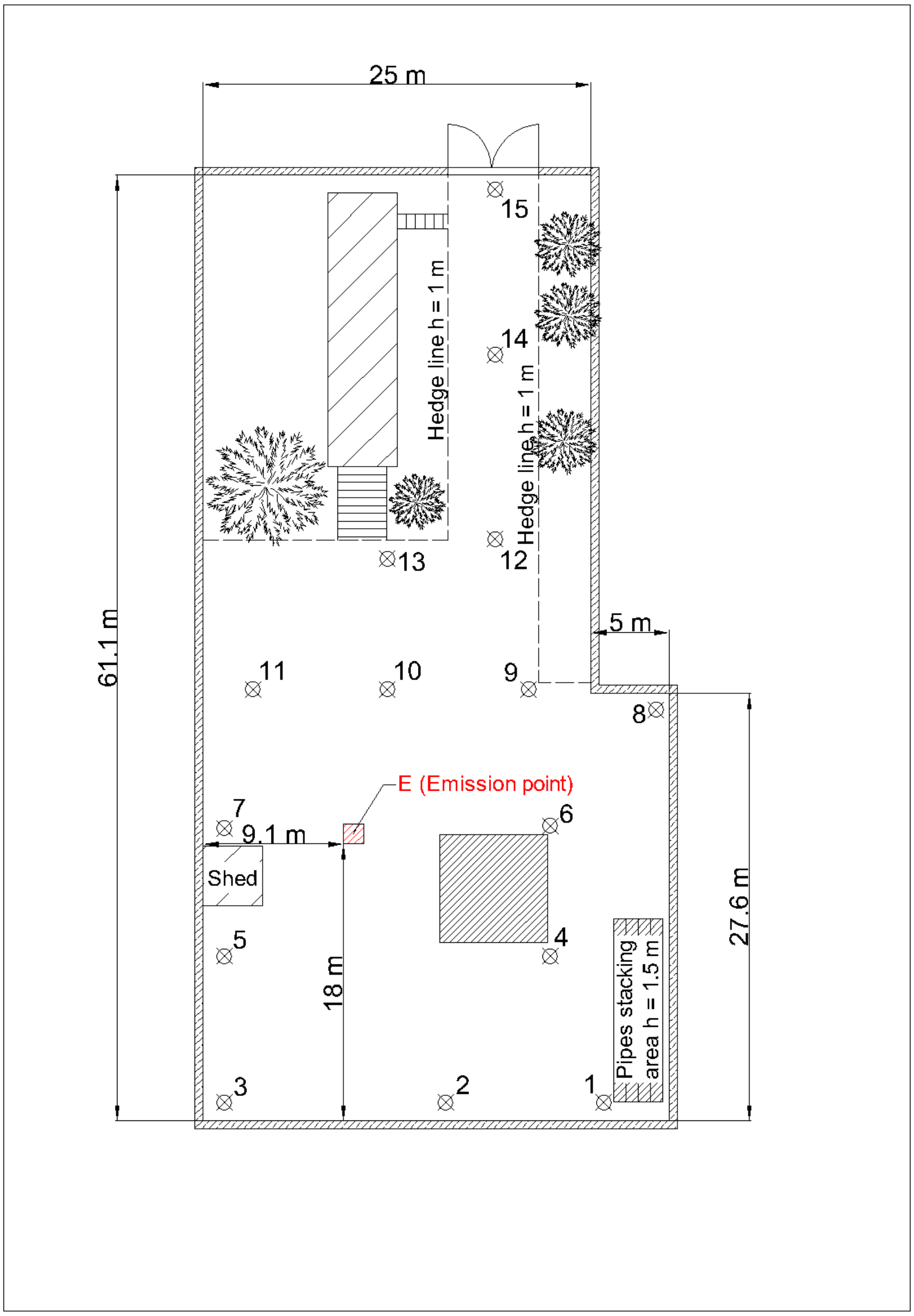

Figure 2. The basis for the model construction, top view of the model (own picture).

The main connection with the atmosphere is a square-shaped hole with an area of 1 m^2.

The area is surrounded by a fence, and inside there is a security and staff building. In the vicinity, there are office buildings and the buildings of the pithead of the former mine. Points marked in Figure 2 with numbers correspond to measuring points.

2.2. The Model

The numerical model and simulations were built in FDS/Pyrosim 2021-1-0224 software (a group of Computational Fluid Dynamics, CFD programs, verified by the National Institute of Standards and Technology, USA [30,31]). It is based on a numerical solution of the Navier–Stokes equations.

The model was built on the basis of previous models [6] and the measuring (in situ) site where the measurements of gas emissions from abandoned mining shafts were conducted within the abovementioned TEXMIN project [1].

Figures 2 and 3 show a general view of the model. They indicate the area covered by the research. On the left and right, the buildings located outside of the area may be noticed. The fence is in yellow. Obstacles in the form of buildings and other objects have been built inside the area, the size of which may affect the direction of gas flow and airflow. The point of emissions is also visible in Figure 3.

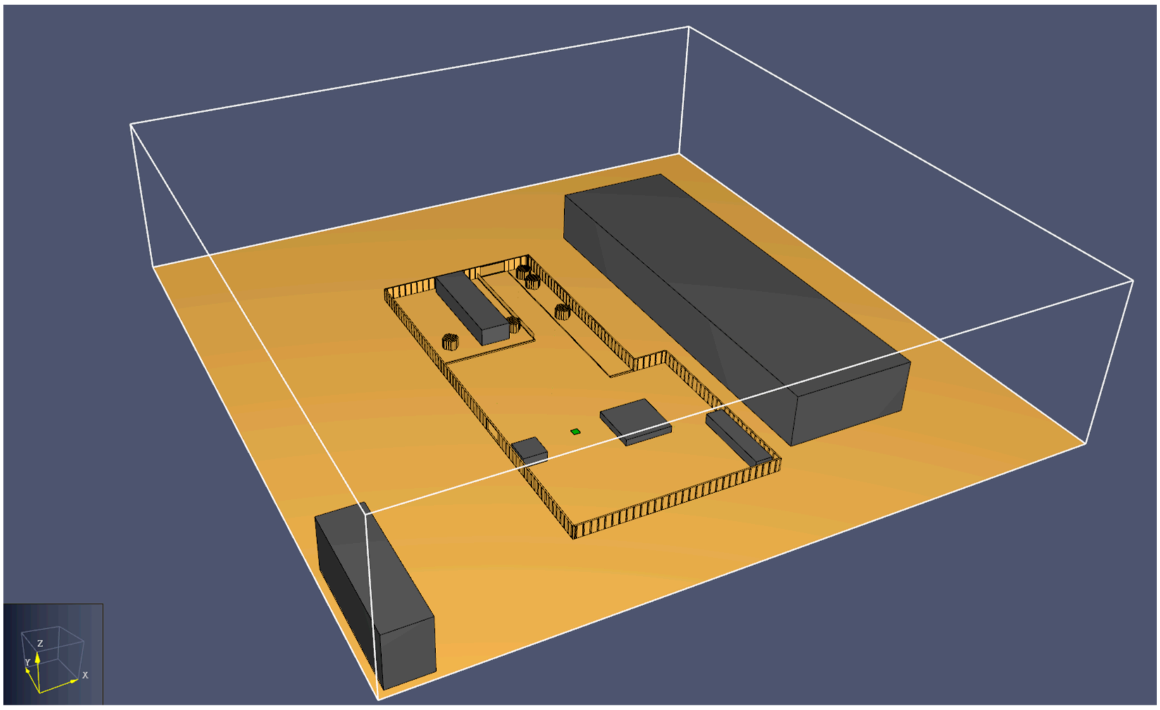

Figure 3. The overview of the model built in the FDS/Pyrosim program. The point of emissions is marked as a green square (own picture).

The model consists of a grid that includes 12,800,000 cells. The size of one cell is 0.25 × 0.25 × 0.3125 m (based on a tool [32]). The following surfaces were implemented in the model:

- Open—which represents the atmosphere. The CO_2 and O_2 concentration was assumed in accordance with the background level differently for each particular variant. CH_4 concentration was assumed as 0.0 vol %.
- Wind—velocity of the wind was assumed specifically for each variant; the profile of the wind was assumed as atmospheric.
- Emissions—the rate of emissions and gas concentrations were assumed on the basis of the previously mentioned measurements.

The following gases were included in the model:

- O_2, CO_2, CH_4, N_2.

The following devices were included in the model:

- 2D slice for O_2, CO_2, and CH_4 at two levels—0 m and 1 m above ground level. A cloud map is the equivalent of an existing measurement situation resulting from unstable atmospheric pressure. When the measurements were carried out, it was found that stable values may last up to approximately 120 s. This time was adopted as the simulation time. After this time, the assumed gas emission parameters should be changed.

Additional obstacles were built, and they were set as INERT.

The Smagorsky coefficient was set as default 0.1. The turbulence solver was set as VLES. An additional tracer was turned on for better visualization of the results. Each variant was computed for 120 s of simulation.

The validation of the model was carried out as simulation variant No. 1. All variants are described in Section 2.3.

2.3. Simulation Variants

Four variants were computed, and the results were obtained for two levels, 0.0 m and 1.0 m above ground level. This corresponded to the method of carrying out the measurements and expected weather events. Variant 1 is a scenario used to validate the model by simulating the weather phenomenon for 26 September 2020 at 19:00. A model corresponding to the situation was built, and the measurement results for individual measurement points were compared with the simulation results. Knowing that the model works properly, it was possible to introduce an additional component, such as methane, and change other gas concentrations as well as the rate of emissions. In variant 2, the maximum concentration of carbon dioxide in the emitted mixture was assumed on the basis of the maximal value detected during the entire series of measurements. The concentration of methane was set corresponding to the lower explosion limit (because the methane was not emitted in situ). The maximal median value for CH_4 detected by Sechman [9] was 2.93 vol %, and it was decided to increase it to a more critical situation. The maximum velocity of emitted gases (from another measurement day) was assumed as well as the minimum detected oxygen concentration (also from another day). This variant corresponds to the worst-case scenario resulting from the measurement data (maximal values taken from different days). Additionally, the absence of wind was assumed, which was also found to be an unfavorable situation for gas accumulation near the shaft. Variant 3 is equivalent to variant 2, but a wind speed of 1 m/s was assumed from one direction (south). It corresponds to the values of this speed found in the dominant south direction (based on previously measured results [5], and it is set to compare with variant 2, expecting that wind velocity is a regular situation during weather events). Variant 4 is a completely hypothetical variant, based on the prediction of maximum concentration when predicting extreme weather phenomena in the future, and it was assumed that the input values could be doubled compared to variant 2. It was also assumed that there was a lack of wind so as to represent the worst situation for safety.

Details about the assumptions are given below:

(a) Variant 1—validation of the model.

Validation was computed for the measured results from 26 September 2020, at 19:00, for the measuring points 6, 8, 9, 11, and 12 (given in Figure 2).

Assumptions for validation variant.

On 26.09.2020, at 19:00, there was an upcoming storm event, and the emitted gas mixture consisted of the following: CO_2 = 8.59 vol %, O_2 = 9.9 vol %, velocity of emissions = 0.31 m/s, N_2 = 81.51 vol %, southern direction of the wind, velocity of wind = 0.3 m/s, pressure drop rate = 1 hPa/h.

Knowing the cross-sectional area of the point of emissions, the rate of CO_2 emissions was estimated as 0.27 m^3/s.

(b) Variant 2—wind velocity 0.0 m/s, CO_2 = 9.0 vol %, O_2 = 4.9 vol %, CH_4 = 5.0 vol %, N_2 = 75.7 vol %, velocity of emissions = 2.86 m/s. Momentary CO_2 emissions for this variant were 0.26 m^3/s. Momentary CH_4 emissions for this variant were 0.14 m^3/s. Wind velocity was set as 0.0 m/s. The lack of wind gives an increased concentration of the gases near the closed shaft. Considering the safety aspects around the decommissioned shaft, this is the least favorable weather situation, although unlikely. During the measurements, it was found that the baric discount is most often associated with the presence of wind.

(c) Variant 3—wind velocity 1.0 m/s, CO_2 = 9.0 vol %, O_2 = 4.9 vol %, CH_4 = 5.0 vol %, N_2 = 75.7 vol %, velocity of emissions = 2.86 m/s.

(d) Variant 4 –The following input data for the simulation were estimated: the maximum expected concentration of CO_2 may be 12.0 vol %, the minimum oxygen concentration 4.0 vol %, and the emissions velocity can reach 5.72 m/s. As in the previous variants, the CH_4 concentration in the emitted gases was assumed to be 5.0 vol %, the lower explosive limit (LEL) for this gas. Wind velocity was set to 0.0 m/s as the worst situation. Momentary CO_2 emissions for this variant could be 0.69 m^3/s. Momentary CH_4 emissions for this variant could be 0.29 m^3/s.

For variants 2–4, the results are presented visually with the colors indicated in the legend.

3. Results and Discussion

(a) Variant 1

Figures 4 and 5 show the comparison between the data gathered during the measurements on 26 September 2020, at 19:00, and computed in the program for carbon dioxide and oxygen.

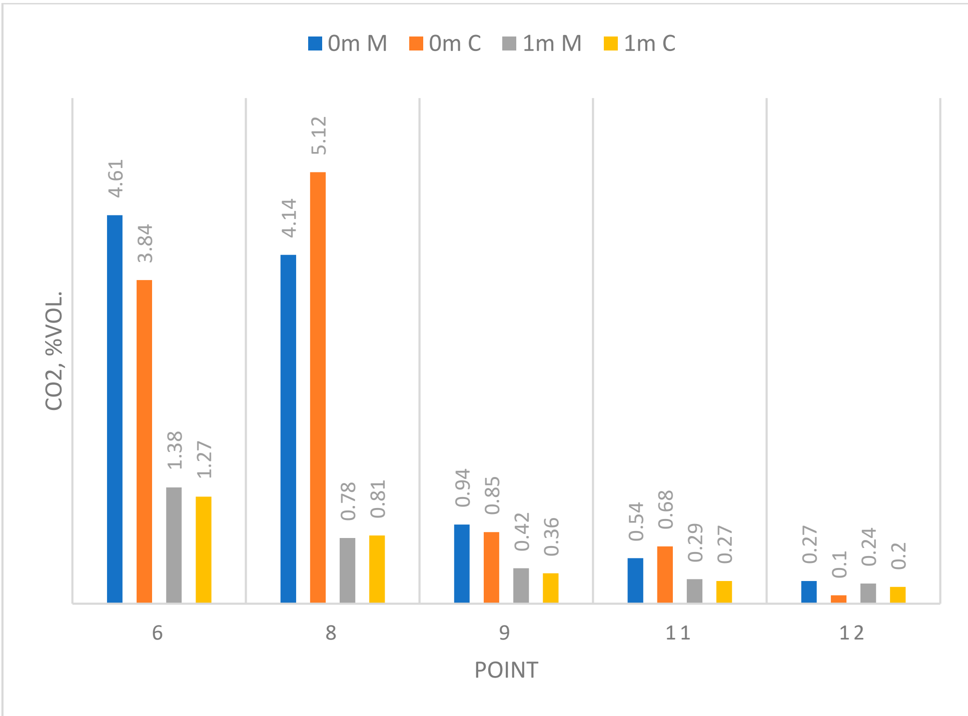

Figure 4. Comparison between the data gathered during the measuring and computing of carbon dioxide concentration on 26 September 2020, at 19:00, near the Gliwice II shaft for selected points, M—measured, C—computed (own picture).

As can be seen from Figures 4 and 5, the results for the validation variant are consistent with the results of measurements carried out in the area of the Gliwice II shaft. The differences between the measured and calculated values for CO_2 range between 0.089 vol % and 0.98 vol % at 0.0 m and between 0.023 vol % and 0.0604 vol % at 1.0 m and 0.8 vol % at 0.0 m and between 0.0 vol % and 0.4 vol % at the level of 1.0 m.

(b) Variant 2

In variant 2, the results were obtained for the three gases: CO_2, O_2, and CH_4 at two levels, 0 m and 1.0 m above ground level. In the case of CO_2, the maximum concentration near the shaft was 3.5 vol % at ground level and 1.0 vol % at the level of 1 m. At the level of 0 m, the area with the higher concentration exceeded the range of 25 m from the point of emissions. Considering CH_4, the maximum concentration at ground level was 2.0 vol %, while at the level of 1 m it was 0.65 vol %. The gas was noticed beyond the boundaries of the measuring area and exceeded the distance 18 m from the point of emission. Considering O_2, the minimal concentration was about 10.0 vol % at ground level, and up to 18 m, there were areas with oxygen concentration lower than 21.0 vol %.

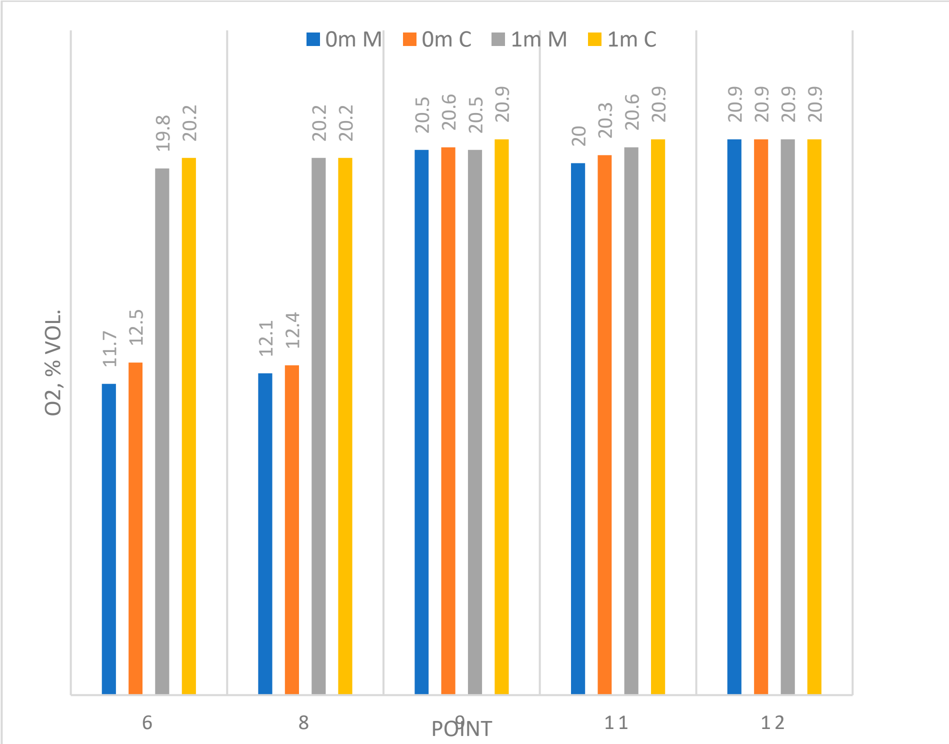

Figure 5. Comparison between the data gathered during the measuring and computing of oxygen concentration on 26 September 2020, at 19:00, near the Gliwice II shaft for selected points, M—measured, C—computed (own picture).

A general conclusion from the analysis of variant 2 is that the lack of wind means that these gas hazards present a risk for this 25 m area around the shaft.

(c) Variant 3

In variant 3, the results were obtained for the three gases: CO_2, O_2, and CH_4 at two levels, 0 m and 1.0 m above ground level. The concentration of carbon dioxide and methane is strongly diluted by the influence of the wind; therefore, oxygen concentration is at the safe level near the shaft. The maximum concentration of carbon dioxide equals 0.06 vol % at ground level and 0.05 at 1.0 m and is slightly above the background value at a distance of more than 50 m from the emission source. In the case of methane, the concentration of methane does not exceed 0.01 vol % in the area of the stream of emitted gases. The concentration of oxygen is reduced to 14 vol % in the immediate vicinity of the emission source (up to 10 m), in the stream of gases.

A general conclusion from variant 3 is that the wind is advantageous in terms of diluting the gases emitted from the shaft. On the other hand, it transports the gases beyond 50 m from the shaft. However, the range of the danger zone here can only be determined on the basis of reduced oxygen content and is about 10 m.

(d) Variant 4

In variant 4, the results were obtained for the three gases: CO_2, O_2, and CH_4 at two levels, 0 m and 1.0 m above ground level. The results are presented in Figures 6–11. In the case of CO_2, for levels 0 m and 1 m, the maximal concentrations were 4.0 vol % (further than 15 m) and 2.0 vol % (further than 25 m).

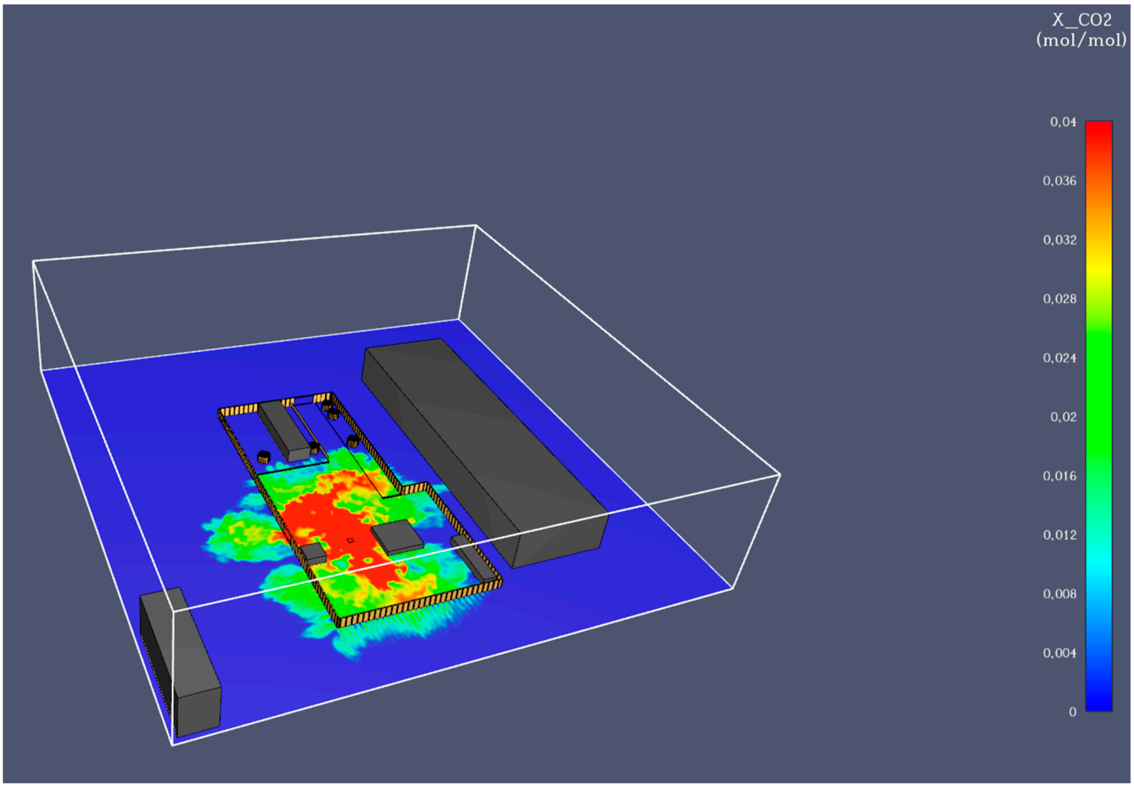

Figure 6. Variant 4—concentration of carbon dioxide near the shaft of Variant 3 at the level of 0 m (own picture).

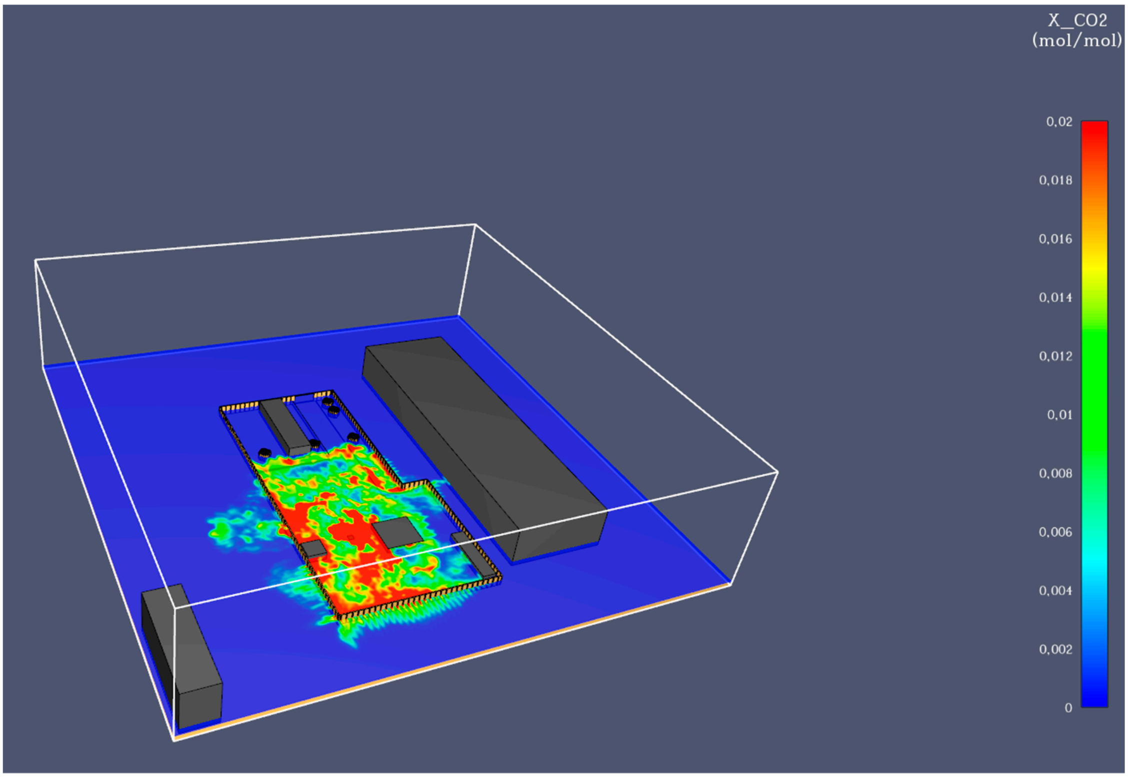

Figure 7. Variant 4—concentration of carbon dioxide near the shaft of Variant 3 at the level of 1 m (own picture).

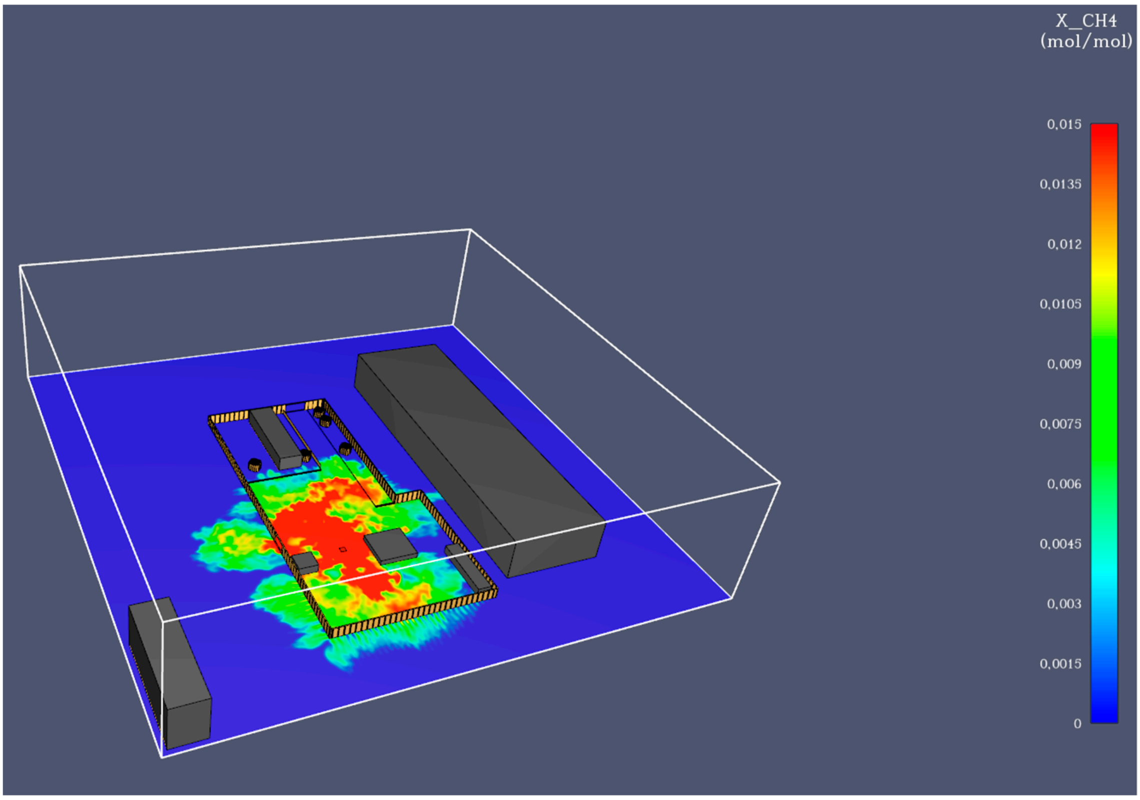

Figure 8. Variant 4—concentration of methane near the shaft of Variant 3 at the level of 0 m (own picture).

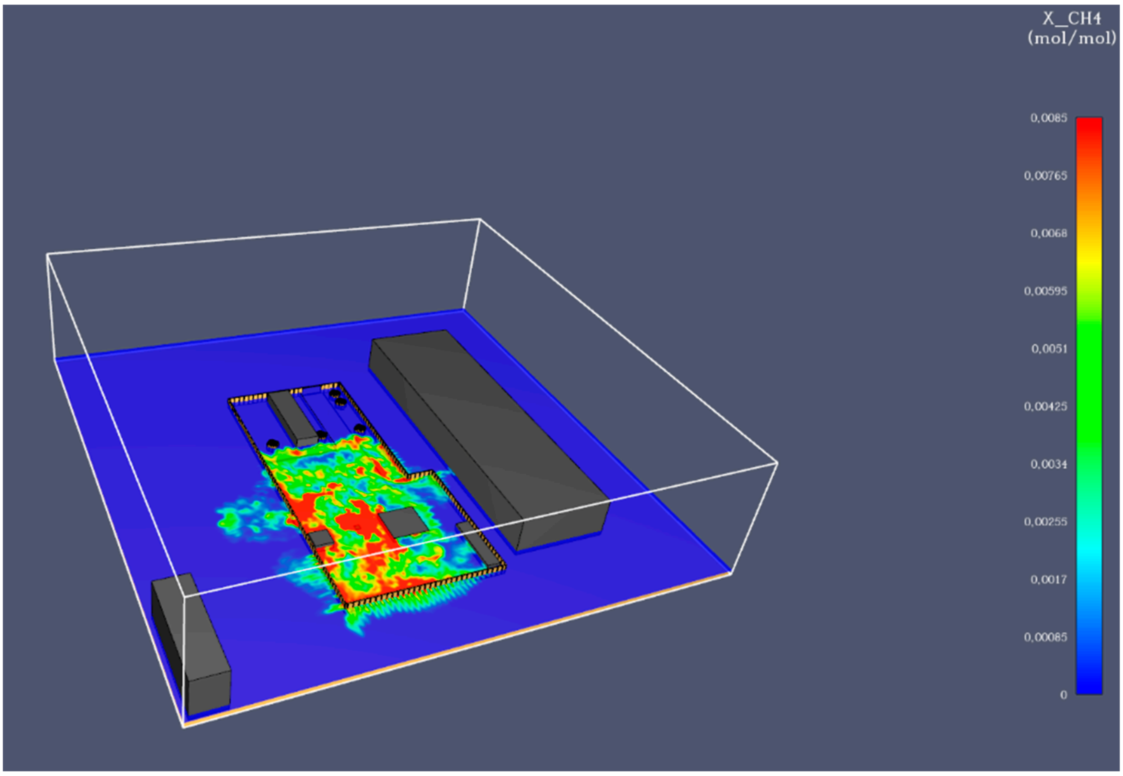

Figure 9. Variant 4—concentration of methane near the shaft of Variant 3 at the level of 1 m (own picture).

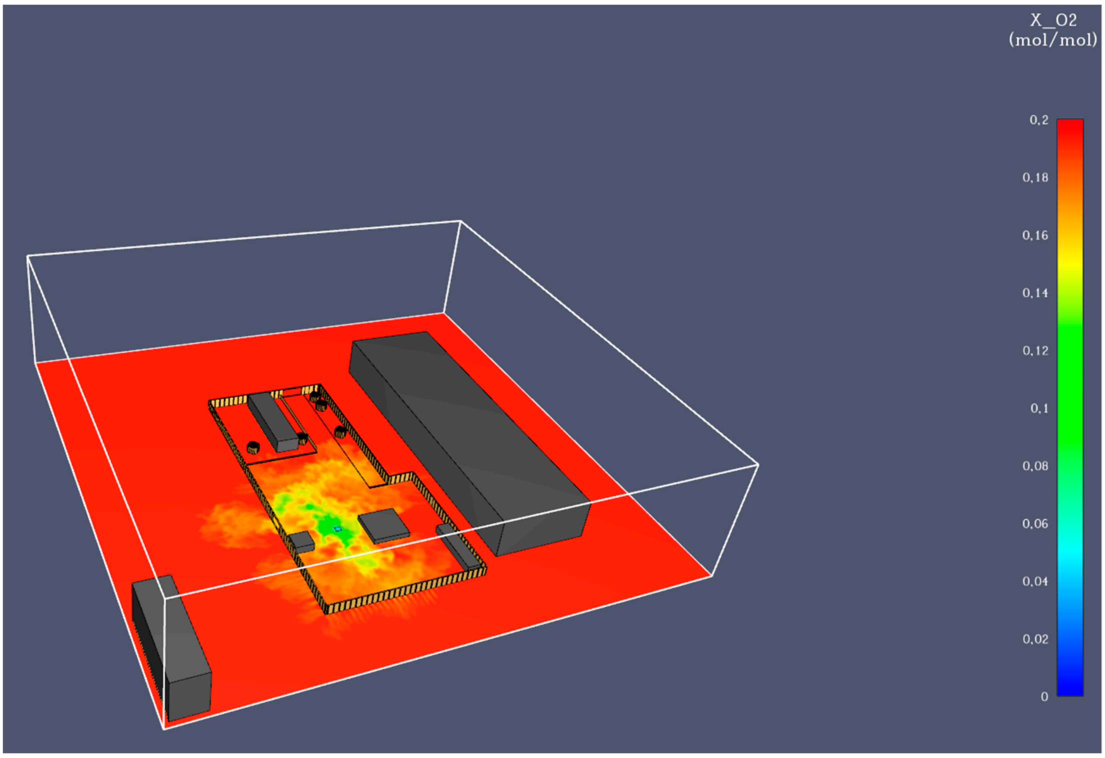

Figure 10. Variant 4—concentration of oxygen near the shaft of Variant 3 at the level of 0 m (own picture).

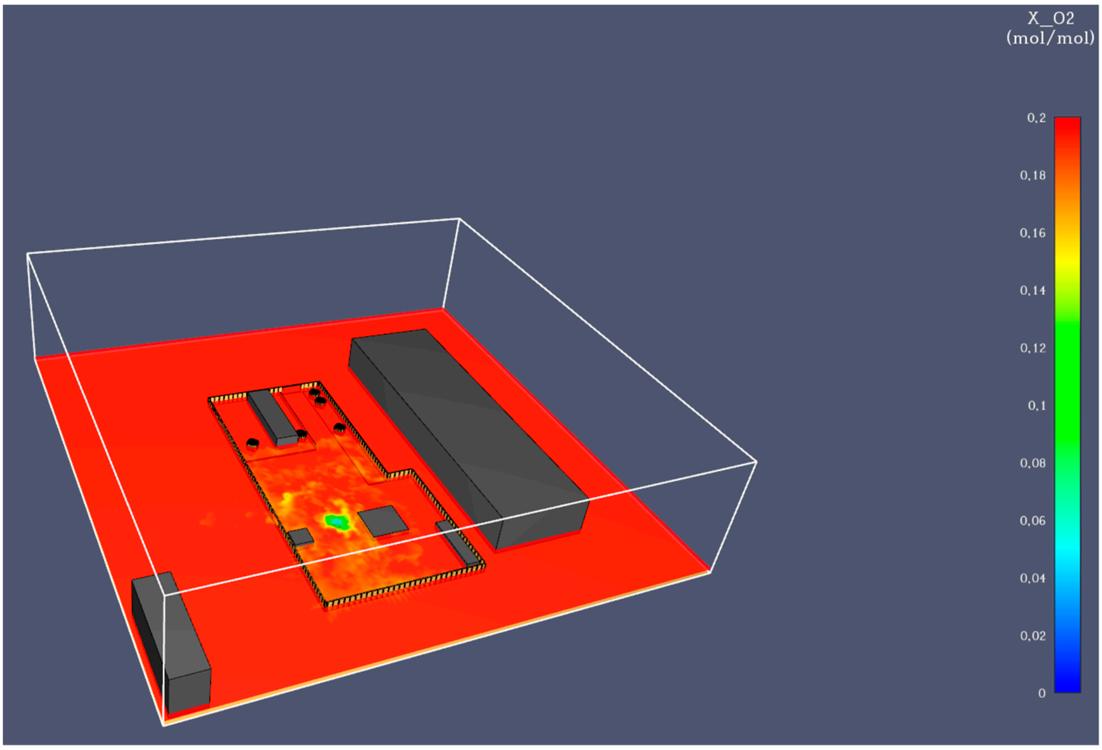

Figure 11. Variant 4—concentration of oxygen near the shaft of Variant 3 at the level of 1 m (own picture).

For CH_4, the concentrations of 1.5 vol % at ground level and 0.65 vol % at the level of 1 m were the highest. It must be noted that 1.0 vol % of methane was detected at a distance of 25 m from the source at this level. At the second level (1 m), it was maximally 0.85 vol %, which exceeded a distance of 15 m from the source.

In the case of O_2, the concentration dropped to about 9.0 vol % at ground level; the range of the zone with reduced oxygen concentration exceeded 25 m.

The results should be related to previous studies on the overall assessment of greenhouse gas emissions.

The results presented in [6] are related to exemplary and hypothetical values assumed in the emitted gas mixture. Therefore, those predicted values differ from those given in this article. Now, using the previously described simulation variants corresponding to the extreme values found during measurements, as well as higher values predicted for weather phenomena related to climate change (in variant 4), these results obtained are reliable and can constitute the basis for determining safety zones in the vicinity of closed-down shafts, left empty for special purposes. Compared to previous results, increased CO_2 and CH_4 concentrations are expected at distances of up to 50 m from the emission point, but in values slightly above the background value due to the strong dilution of gases by the wind. In the case of variant 4, i.e., the absence of wind, the zone with increased CO_2 concentration may exceed 25 m, and in the case of CH_4 and O_2, it reaches 25 m. In the case of oxygen, this is the zone with reduced content. It leads to the conclusion that 25 m from the decommissioned shaft may be a critical distance at which a gas hazard should be expected. Although these gases can be transported over 50 m by the wind, they are significantly diluted by the wind to safe concentrations.

With regard to methane emissions from an abandoned shaft, reference can be made to the current research results on methane emissions in the area of Upper Silesia, presented in [28,29]. These studies concerned coal mining activities and related methane emissions in the Upper Silesian Coal Basin (USCB). The authors showed that the emission level may vary between $414 \cdot \times 10^3$ Mg CH_4/year and even $720 \cdot \times 10^3$ Mg CH_4/year. Converting $720 \cdot \times 10^3$ Mg CH_4/year into the value of per-second emission, taking into account the methane density of 0.657 kg/m^3, it gives 0.56 m^3/s. The result can be compared with the CH_4 emission for variant 4, which was 0.29 m^3/s; however, it should be noted that the emission from gases from the inactive well is momentary and cannot be reliably related to hourly values and certainly not to annual values. The results of experimental research by Zgadzaj [33] reported that the average carbon dioxide emissions from one mine in the part of Upper Silesia located near the Gliwice II shaft could amount to 0.68 m^3/s, when for variant 4 it is 0.69 m^3/s. Sechman and others [9] pointed out that selected statistical parameters of methane and carbon dioxide concentrations in gas samples measured in the area of Chwałowice Trough and in the vicinity of abandoned shafts I, III, IV, and VII for the closed 1 Maja coal mine were for carbon dioxide 0.4–2.46% (mean value), for methane 0.0002 vol %–9.19 vol % (mean value). Therefore, maximal median values for CO_2 and CH_4 were 3.4 vol % and 2.93 vol %, respectively

4. Conclusions

The paper presents the results of numerical simulations of gas emissions from an empty mine shaft. Simulations were carried out in variants, taking into account the occurrence of severe and violent weather phenomena. The results are important in two ways: firstly, in terms of greenhouse gas emissions from the tested facility, and secondly, in terms of public safety in the vicinity of the closed shaft. In this case, the issue may be important for future pro-ecological technologies that are based on the use of underground cavities in the rock mass. The presented research results are intended to raise awareness of the growing importance of this problem in the context of climate change, especially among decision-makers in the area of decommissioning mining facilities and the future transformation of these areas. It is also important to raise the scientific discussion in the context of the development of appropriate countermeasures to reduce the risks associated with sudden gas releases.

The results lead to the following conclusions:

1. Considering the emission of CO_2 and CH_4 as greenhouse gases, for the most unfavorable variant (Variant 4), this showed that CO_2 emissions for this variant could be 0.69 m^3/s temporarily. Momentary CH_4 emissions for this variant could be 0.29 m^3/s. For one hour of sustained decline of this intensity, this could correspond to 2484 m^3 of CO_2 and 1044 m^3 of CH_4.

2. When there is no wind, there is a gas hazard that affects public safety near a closed shaft. The results showed that this gas hazard may be present up to 25 m from the source (Variant 2 of simulations).

3. On the one hand, the presence of wind dilutes the gases, but on the other, it transports them beyond 50 m from the source according to the direction of the wind (Variant 3 of simulations). However, the range of the danger zone can be determined only on the basis of the reduced oxygen content near the shaft, and it was about 10 m.

4. For the worst weather event scenario (Variant 4 called "what if")—maximal or minimal (for oxygen) concentrations for CO_2, CH_4, and O_2 were as follows: 4.0% by volume at ground level and 2.0 vol % at the level of 1 m, 1.5 vol % at ground level and 0.65 vol % at the level of 1 m and 9.0 vol %. However, at a distance exceeding 25 m, the concentrations of CO_2 and CH_4 were still high, approximately 2.0 vol % and 1.0 vol %, respectively, which leads to the conclusion that in this variant the range of the danger zone exceeds 25 m.

5. As a general conclusion and recommendation, it could be stated that every abandoned shaft must be considered as a place where gas risk and greenhouse gas emissions can be expected during low pressure which will be connected with extreme weather events, which can be expected to increase due to climate change. To mitigate the risk, when filling the shaft is impossible, it is necessary to apply drainage with a gas capture system and apply a proper gas monitoring device connected with ventilation for places where people may be present.

In summary, the TEXMIN project concerned the impact of weather phenomena resulting from climate change on mining activities and activities in post-mining areas. The emission ranges of individual gases and the zone with reduced oxygen content determined during the implementation of tasks related to gas emissions are useful in risk assessment procedures in the post-mining area. These procedures should be taken into account when assessing the safety of such an area in terms of future construction investments and also when using underground post-mining voids for other tasks, e.g., CCS technology or energy storage in compressed air.

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