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METHANE HAZARD DURING THE CLOSURE OF MINE EXCAVATIONS IN LIQUIDATED MINE – NUMERICAL SIMULATION

The closure of deep mines, featuring multi level seam extraction, lasts many years. During this time period, the ventilation system must ensure adequate working conditions, and ensure the safety and stability of fan operation in gas and fire hazards conditions. The analysis of air flows and methane inflows during the progress of mining mine excavations closure, is the primary object of the article. Execution of such analysis requires knowledge of the mining mine excavations' closure schedule, the structure of the ventilation system under consideration, the values of the parameters describing the air flows delivered to the mine excavations, and the current characteristics of operating fans and predicted methane exhalation. A computer database, currently being updated by a mine ventilation department for the *VentGraph-Plus* computer software, has been used simulate the various ventilation scenarios experienced, during the final stage of closure, including the shutdown of the main fans and the backfilling of shafts. The results of case study, containing 2 variants of simulated examples, are presented in the form of diagrams of methane concentration changes in time at characteristic places of the mine. The completed simulations of ventilation processes during the closure of mine excavations and transfer of inflowing methane, indicate useful possibilities of the computational tool used.

Keywords: Mine closure; mine ventilation, network simulators, methane hazard; shut down of main fans

1. Introduction

The functioning cycle of mines also covers their closure stage. The whole system of underground mine excavations finally decays, but the time it will take place depends to significant degree on human intervention. The known research has resulted in guideline rules and guidebooks

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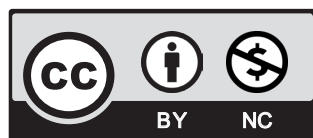
of procedures for safe closure of mine excavations and shafts of decommissioned mines being developed in England [1], Australia [2], Czech Republic [3,4], France [5,6], Finland [7], Canada [8], and in the USA [9]. However, despite the tests and monitoring of gas emissions following the closure of mines being conducted around the world, one can notice that methodology of gas hazard analysis, arising from goafs gases (methane, carbon dioxide) during the process of building a mining seals and backfilling the mine excavations and shafts of mines, is missing [10-17].

The closure of mine excavations, following exhaustion of mineable reserves, is one of the many stages of mine production cycle. This is a routine process, during which a number of actions, aimed at safeguarding mine ventilation system and the atmosphere at the surface against potential uncontrolled gas emissions from closed mine excavations, are executed. The mine excavations being closed are isolated from the remaining part of the mine by damming them up and leaving suitably thick insulating layers in the rock mass. The void space within the abandoned mine excavations can be filled or left unfilled, allowing them to eventually collapse or flood. However, during every coal mine closure, mine shafts are competently backfilled with rock material and usually concrete capped on the surface. The period during which the mine shafts are backfilled is particularly hazardous as the ventilation air flows within the mine are significantly restricted, once the main ventilation fans are stopped. There is one recently reported case of methane explosion during the backfilling of shaft III at the Morcinek mine in 1999 http://kwkmorcinek.pl/index.php?s=historia7).

Between the stages of the original fully operational mine and auxiliary ventilated mine ventilation system and the final full closure, there is a process of gradual, stage-wise closure of underground mine mine excavations [18]. In addition, there may also occur circumstances that require reduced ventilation , delivery including the use of a heading for equipment storage. Changes in the structure of mine excavations also influence demand of ventilation power. This is the reason why the adaptation of fans to varying demand is necessary, thus ensuring conditions of their effective and safe operation. The closure process should be preceded by an adequate analysis of the staged ventilation process required, which determines the manner of its execution, particularly in the aspect of the methane hazard during mine excavations closure [18]. The premises for developing guidelines regarding ventilation systems and gas hazards prevention should be included in the framework of the complete abandonment hazard assessment [19].

The paper presents an analysis of the potential methane hazard that may be experienced during the final closure stage of one of the Polish hard coal mines. Particular attention was given to potential gas hazards related to ventilation systems of deep mines, resulting from the transfer of goaf gases to the surface and their influence on neighbouring mines.

2. The object and methodology of the research

An interesting issue is the attempt to assess the methane hazard level of the "A" mine being closed, with consideration given to methane inflow from the longwall workings closed during the years 2005-2017 longwalls, within the coal seams 703/1-2, 707/1-2, 713/1-2 and 718/1-2. It has been assumed, on the basis of available seams maps and gas content analyses, that methane emissions were present within the mine excavations located at 800 and 1000 m levels (Fig. 2). The determination of the transient methane concentration changes experienced over time at the terrain surface of the "A" mine being closed, and the value of this methane concentration, was the primary objective of the research.

In order to achieve the aim of the research, the numerical simulation method was assumed [20] with use of the *VentGraph-Plus* computer software package [21-25].

The mathematical model was adapted to consider the changes of natural reduction in ventilation due to methane inflow, that permits the determination of the ventilation and methane concentration transients experienced in the part of the mine "A" being closed [26] and also within the adjacent and connected still functioning mine "R-A". The combined "R-A" mine is composed of Operation I (R) and Operation II (A). The "A" mine was systematically closed, starting from 2005, by the gradual closure of mining operations in the west part of the mine within the 800 and 1000 m levels, where mined longwalls have been ventilated to the Jedłownik and the Ryszard II shaft, located to the east part of mine. Fig. 1 shows the diagram of the combined "R-A" mine structure of mine excavations in 2005. Following closure of the Jedłownik shaft in 2012, the east part of the mine and existing, vast goafs have been exposed only to the depression of the Ryszard II ventilation shaft. Furthermore, in this time period, the Jan downcast shaft was closed, and then in turn the Chrobry II shaft was closed. It was assumed that the methane emission from closed longwal goafs, aided by ventilation, had flowed into the east part of the mine, towards the Ryszard II shaft.
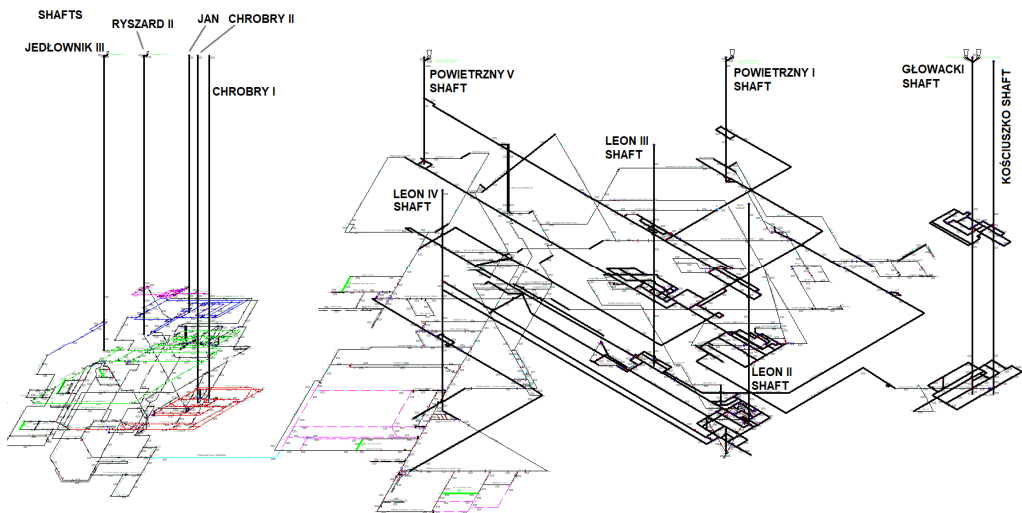

Fig. 1. Ventilation scheme of the combined "R – A" mine, year 2005

The closure process of the subsequent mine excavations and longwalls in the "A" mine was ongoing on July 30th, 2017. Fig. 2. illustrates the mine's structure at that particular time. During this period, the ventilation of the "R-A" mine was restricted to a single underground the "R draining dip-mine excavation in the 713/1-2 seam". At the beginning of 2017, the mine ceased the operation of the last R-15 longwall, then the ventilation services of the "A" mine shut down the fan (06.29.2017) working on the Ryszard II shaft, which started the last closure stage of the "A" mine by backfilling the Chrobry I downcast shaft and the Ryszard II shaft. Simultaneously, liquidation work has been performed, leading to the ventilation isolation of the "A" and "R" mines by making a water dam within the "R draining dip-mine excavation in the 713/1-2 seam" (Fig. 2).
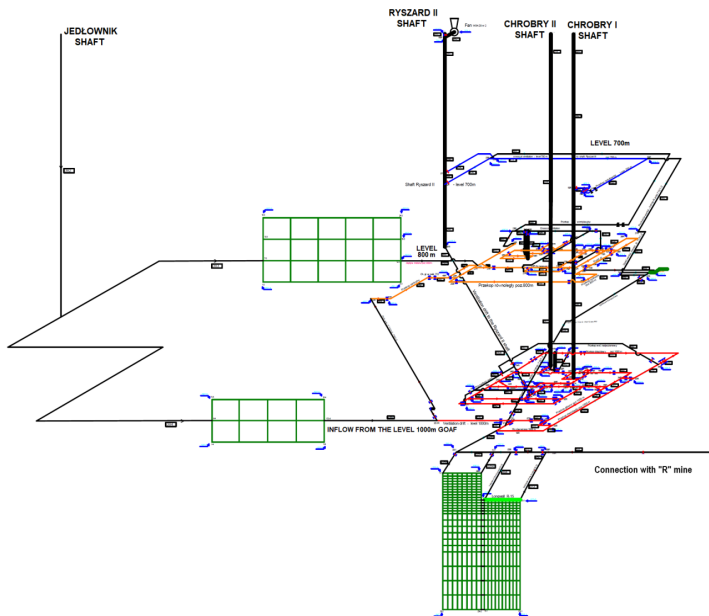
Fig. 2. Numerical model of the ventilation system of the "A" mine including
the old goafs for level 800, old goafs level 1000 m and goafs of longwall R-15

Until the fan shut down in the Ryszard II shaft, the volume of methane emitted from the "A" mine was the function of air flow rate output from the mine and the concentration of gases on the Ryszard II shaft outlet. Following the fan shut down, the methane hazard related to further closure process is a function of the resistance resulting from closing shafts by backfilling them, the natural depression value (the thermal and gas one), the volume of methane exhaled from goafs at 800 m level and 1000 m level, and resulting from that, changes of gas volumetric concentration in the spaces of the mine being closed. The date of 30.11.2018 is assumed as the ventilation time point of the "A" mine closure, that is, the closure of the Ryszard II and Chrobry I shafts by pouring out concrete slab on the shaft top following backfilling it and leaving the inspection gate and 150 mm diameter pipe for venting.

The above presented description of actions during closure of the "A" mine, starting from the time of the fan shut down on the Ryszard II shaft, proceeded slowly, taking 16 months of backfilling of the Chrobry I and the Ryszard II shafts, making the water dam and the construction of concrete slab on the tops of both shafts, will constitute the base of the ventilation actions schedule, assumed in the numeric simulation process of the air and methane flow distribution, with simultaneous restriction of air flow in the structure of mine ventilation network.

2.1. The characteristics of methane inflow at the 800 m level and 1000 m level

The significant factor of methane emission hazard assessment during the proceeding closure of mine excavations, is the determination of methane inflow characteristics. The prognosis of

methane inflow in mines being closed is determined on the grounds of methane desorption tests, performed by the researchers [11,14,26,28,29]. The interesting research was performed by the authors of the paper [30], where long-term prognosis, 2017 until 2032, of methane emission in conditions of the "A" mine under closure, was presented. Based on this research, the total volume of goaf for the mine excavations of the mine under closure was estimated at 11.5×10^6 m³, and, on the grounds of additional information, obtained from the "R-A" mine services, it has been found, that methane inflow within 2017-2032 from abandoned longwalls and their extensive old goafs was determined for the seams 703/1-2 (9 longwalls), 707/1-2 (11 longwalls), 713/1-2 (9 longwalls), 718/1-2 (3 longwalls) mined at the 800 m level and at the 1000 m level. For the purposes of numerical simulation, data related to methane exhalation from each seam were approximated with polynomials, and the results are presented in the subsequent figures.

1. Inflow to the level of 800 m, total goaf volume 6.5×10^6 m³, decaying methane inflow characteristics according to the Fig. 3, from seams 703/1-2, 707/1 and 718/1-2.
2. Inflow to the level of 1000 m, total goaf volume 3.6×10^6 m³, decaying methane inflow characteristics according to the Fig. 4, from seams 703/1-2, 707/1-2 and 713/1-2.
3. Supply of methane to goaf of the abandoned R-15 longwall, total goaf volume 1.4×10^6, decaying methane flow characteristics according to the Fig. 5, R-15 longwall, 713/1-2 seam.

The determined characteristics of methane inflow (Figs. 3-5) were approximated by sections with polynomials, and used as an input into *VentGraph-Plus* simulation program and then attributed, respectively, to goaf connected with the 800 m level and the 1000 m level and with goafs of R-15 longwall at the 1000 m level. An uniform distribution of inflow of methane to the area of goaf is assumed. It is significant for the simulation process to assume adequate geometry of goafs in the numerical model, to obtain the calculated volumes of the goafs corresponding to them [20,31]. The numerical model built in this manner enables us to take into consideration the diminishing methane inflow during the simulation of the methane transport process in the goafs, and then in the mine excavations of the "A" mine under closure.
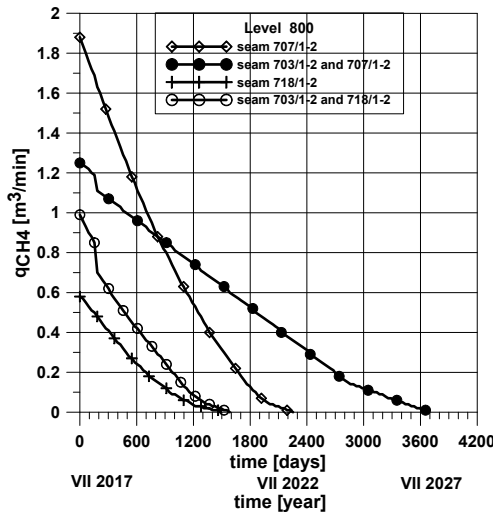

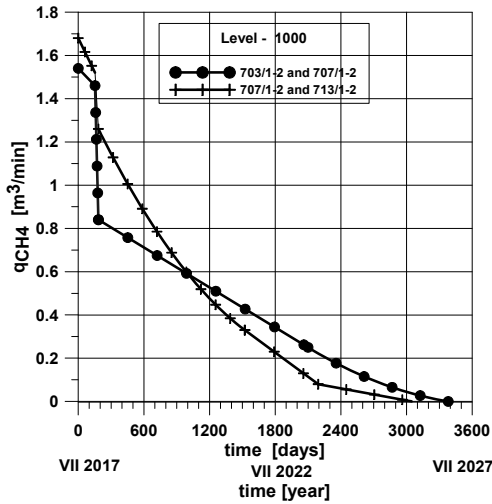Fig. 3. Methane inflow characteristics at the level 800 m

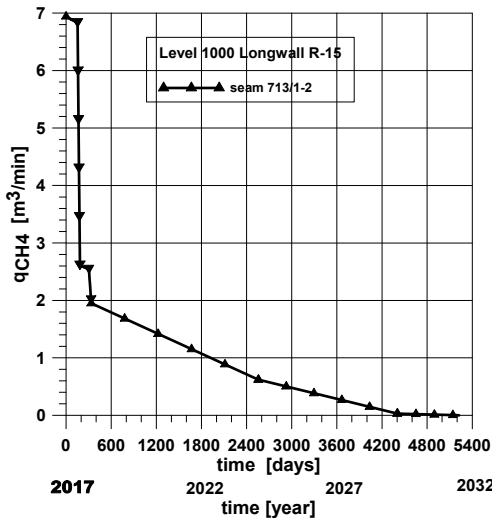Fig. 4. Methane inflow characteristics at the level 1000 m

Fig. 5. Characteristics of methane inflow to goaf of the abandoned longwall R-15

3. Closure of the "A" mine mine excavations, ventilation shut down – numerical simulation

To simulate flow phenomena with *VentGraph-Plus* software, one should prepare a dataset containing the set of ventilation parameters, identifying the structure of mine excavations together with goafs, with consideration given to methane inflow. The mathematical model used in the *VentGraph-Plus* software was the subject of many publications [24-26]. Preparation of

database for numerical model determination (Fig. 2) was preceded by an analysis of materials obtained from the mine.

It was assumed that the considered network region of "A" and "R" mines consists of abandoned R-15 longwall, 713/1 seam, and its goafs, as well as of mine excavations at longwall, the mine excavations of the shaft bottom at the 1000 m level, 800 m level and 700 m level, including the Ryszard II and Chrobry I shafts, and the extensive goafs located in the east part of mining area, earlier abandoned longwalls in the years 2005-2017 and having ventilation connection to the mine excavations at the 800 m level and 1000 m level. Fig. 2 shows the numerical model of the "A" mine, presenting the simulation structure of the above-described mine excavations, supplemented by additional mine excavations of goafs of the 800 m level and 1000 m level, which are shown in the form of two green polygons, and the goafs of the R-15 longwall are located underneath.

The data, characterising flow of the air and methane mixture for the mine excavations, were determined on the grounds of ventilation measurements, performed in the network of the mine mine excavations in 2016. A different procedure is used for determining data characterising flow in goaf. Because the possibilities of performing measurements directly in goaf do not exist, in order to determine parameters of the model, one can use theoretical model of permeability distribution and height of goaf shaping [20], and information contained in the map of seams, geological profile of the region, design of longwalls mining (geometry, spot heights of levelling, thickness of the seam being mined, type of roof rocks). Considering methane inflow to the area of mine excavations at the 800 m level and 1000 m level, including abandoned R-15 longwall, the simulation of the air and methane flow distribution in ventilation network was conducted in time-loop with use of **Symulacja** (Simulation) module of the *VentGraph-Plus* software package. Two areas of extensive goaf, having connection with shaft bottom at the 1000 m level and 800 m level, were designed to consider long-term methane inflow. Furthermore, the geometry of the goaf was selected, so that total volume of goaf (11.5×10^6 m^3) corresponded to values resulting from methane inflow characteristics assumed [30].

The complex problem of shaping gas atmosphere at varying conditions of ventilation and methane inflow to the mine excavations of the "A" mine under closure is considered. Flow velocities of the air and gases mixture and distribution of methane concentration in goafs is forced by operation of main ventilation fan, installed on the "A" mine shaft and on the "R" mine shafts. After the shut down of the Ryszard II fan a significant role in flow distribution of the mixture took over the natural depression, which is generated by methane flow in the mine excavations and connection with neighbouring "R" mine. As mentioned above, mutual interactions influence the air flow distribution and concentrations of individual components of goaf's and mine excavations' atmosphere of the "A" mine. As shown in the Fig. 1, the "A" mine (the mine excavations on the left side of spatial diagram) is connected through the "R draining dip-mine excavation in the 713/1-2 seam" with the mine excavations of functioning "R" mine (the mine excavations on the right side of the Fig. 1). The "R" mine is ventilated by means of three ventilation shafts, which results in that the "A" mine excavations under closure being influenced by the depression created for ventilation of the "R" mine. An interesting case is the verification of methane migration directions in the "A" mine under closure, in the case of ventilation shut down for the neighbouring "R" mine. To illustrate this case, the proceeding scenario for the air and methane mixture flow distribution simulation during liquidation of the "A" mine excavations was modified in such a manner that, after a two-years lapse, the fans operating on the "R" mine ventilation shafts were shut down.

Within the frameworks of example I, we consider the air and methane flow distribution computations scenario, resulting from introduction the following, subsequent actions in course of the computer simulation:

- Step 1 – after 5 days passed from the simulation beginning, the fan operating on shaft Ryszard II was shut down.
- Step 2 – after 10 days passed from the simulation beginning, the following actions were started:
  - Simulation of damming up the "R draining dip-mine excavation in the 713/1-2 seam", the final resistance of the 666 [Ns^2/m^8] by building mining dams was obtained in 6th simulation month.
  - Simulation of the Chrobry I shaft backfilling, by increasing resistances of subsequent section of the shaft up to 666 [Ns^2/m^8] value; the ultimate sealing up the shaft was ended in the 12th simulation month.
  - Simulation of the Ryszard II shaft backfilling, by increasing resistances of subsequent section of the shaft up to 666 [Ns^2/m^8] value; the ultimate sealing up the shaft was ended in the 16th simulation month.
  - Simulation of producing concrete slab for the Chrobry I shaft and the Ryszard II shaft, dam resistance 500 [Ns2/m8], execution time from the 8th until the 12th month.

The action scenario of fan shut down on the Ryszard II shaft and sealing up the Ryszard II and Chrobry I shafts and connection with the "R" mine, was executed during 16 months of real time.

For example II, the computations were conducted in the identical manner as for example I, and then, after a 2 year lapse from the time of fan shut down on the Ryszard II shaft, step 6 was introduced, consisting in simulation of shutting down fans on the shafts of neighbouring "R" mine.

3.1. The simulation of the air and methane flow distribution during closure of the "A" mine shafts – examples I and II

In order to present possible solutions with the *VentGraph-Plus* software, two examples of the air and methane mixture flow distribution simulations have been performed, with consideration given to scenario of backfilling shafts and main ventilation fans shut down. Additionally, for example II, the scenario assumes, that following two years of simulation, shut down of fans in neighbouring "R" mine will be done. This enabled us to obtain solutions of different methane hazard degree and a wider assessment of higher methane concentrations occurrence risk on the surface of the "A" mine area under closure.

The presentation of obtained simulation results was shown jointly for two examples in graphical form, in the subsequent time points of the process of restricting air flow in the network of mine excavations. Fig. 6 presents the air and methane flow distribution for the condition preceding fan shut down on the Ryszard shaft prior to closure of the Chrobry I shaft, and the connection with the "R" mine.

The results of computations will be presented on graphs of methane concentration changes in time, recorded by virtual sensors of *VentGraph-Plus* program [25]. For the assumed initial conditions, in every time step computation of the air and methane flow distribution takes place and methane concentration distribution in the mine excavations is also computed (10 sec. time step, 4 years computation period). After computation of inflowing methane concentration has been done, the density distribution of the air and methane mixture flowing in every mine excavation
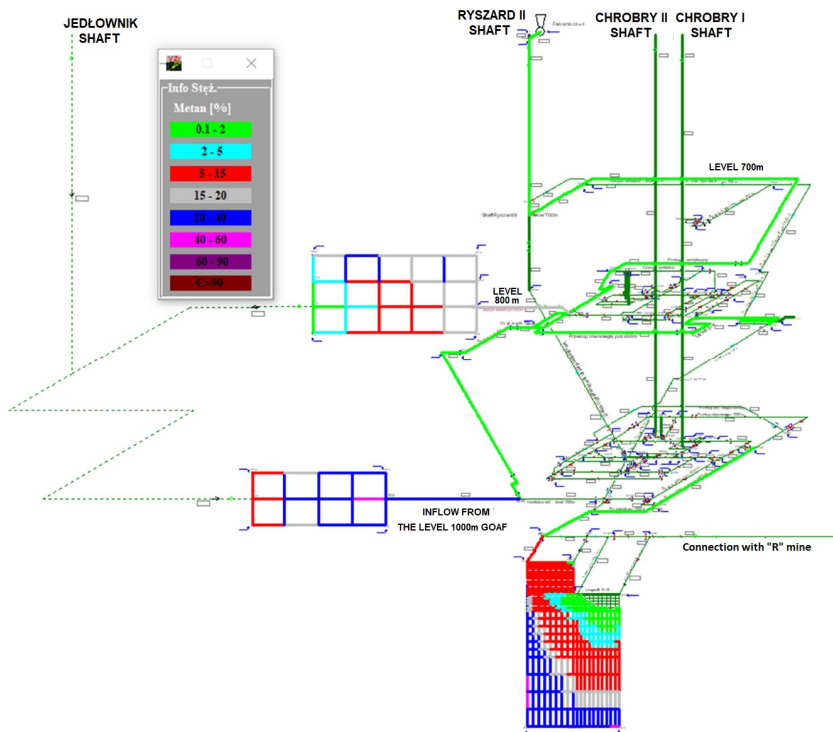
Fig. 6. The air and methane mixture flow distribution, initial state July, 2017 – fan on the Ryszard II shaft operating, bold lines represent methane concentration level acc. to colour scale shown

and in goaf is determined, and, in consequence, the new value of natural depression resulting from the methane inflow. The depression computed in each time step constitutes the base for determining flow rate value in the next time step. With progress of the computations, the results from individual transitional states are stored in disk files, which enables the preparation of graphs in the location places of the virtual sensors of flow rate and methane concentration.

To image development of ventilation process during actions of mine excavations sealing up , virtual methane sensors and volumetric flow sensors of the air and methane mixture in characteristic mine excavations of the mine were installed:

- in the Ryszard II shaft, in the fan duct – concentration of methane and air volume,
- concentration of methane and air volume in the "R draining dip-mine excavation in the 713/1-2 seam", being a connection with the "R" mine.

In the subsequent figures from 7 up to 10, the process of methane concentration changes during closure of mining mine excavations of the "A" mine, determined by computer simulation, is shown, where the black broken curve for example I, i.e. continuous operation of fans on the neighbouring "R" mine, while the red curve, for example II, represents, i.e., the shutdown of fans operation after two years simulation on the neighbouring "R" mine.

In the subsequent Fig. 8, changes of methane concentration in the fan duct of the Ryszard II shaft are shown for the two simulated examples.
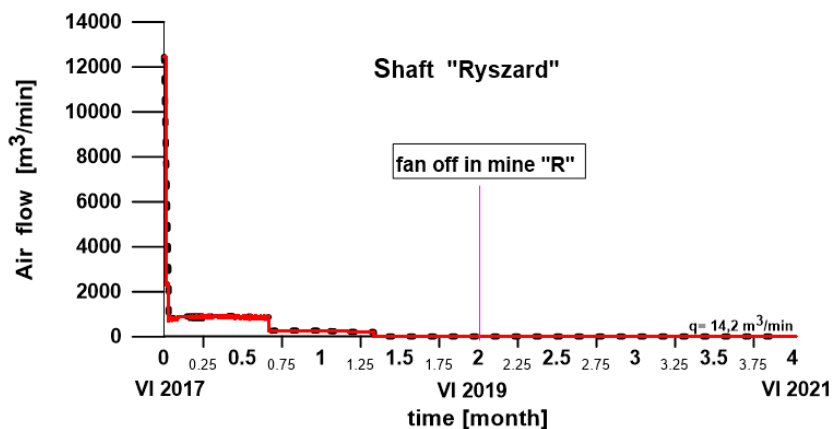
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Fig. 7. Changes of air volume at outlet of the Ryszard II shaft;
– the black broken curve, the fans in the "R" mine are operating,
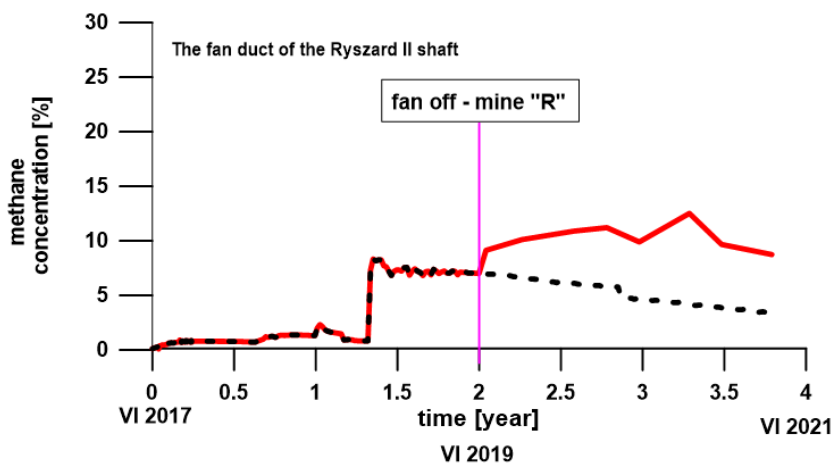– the red curve, shut down of the fans in the "R" mine

Fig. 8. Changes in methane concentration in the fan duct of the Ryszard II shaft;
– the black broken curve, the fans in the "R" mine are operating,
– the red curve, shut down of the fans in the "R" mine

Fig. 9 presents changes of methane concentration in the "R draining dip-mine excavation in the 713/1-2 seam", connecting the "A" and "R" mines.

Fig. 10 shows volume changes of the air and methane flowing in the draining R dip-heading in the 713/1 seam, connecting both mines. The visible change of the air and methane mixture flow direction is characteristic; the mixture directs itself to the mine excavations of abandoned "A" mine (Fig. 10).
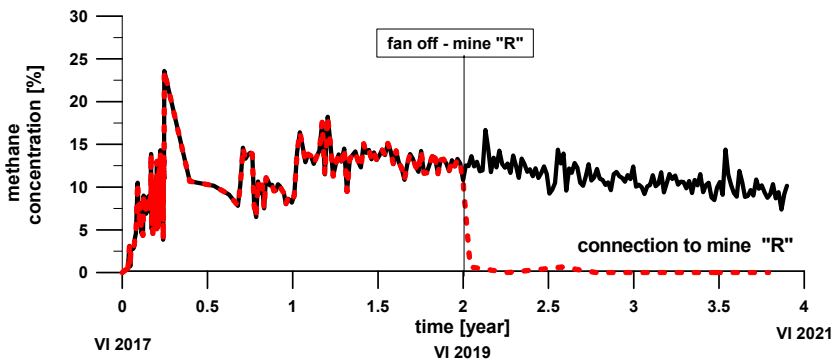
Fig. 9. Changes of methane concentration in the "R draining dip-mine excavation in the 713/1-2 seam";
– the black broken curve, the fans in the "R" mine are operating,
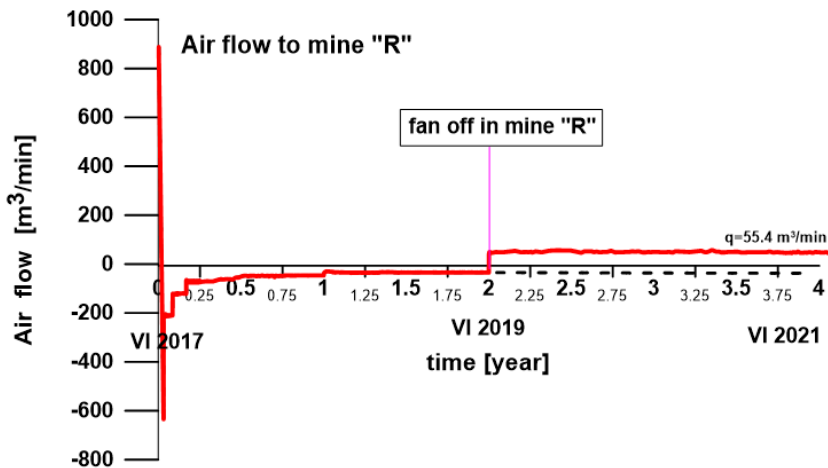– the red curve, shut down of the fans in the "R" mine

Fig. 10. Changes of the air and methane volume in the heading connecting the "A" and "R" mines;
– the black broken curve, the fans in the "R" mine are operating,
– the red curve, shut down of the fans in the "R" mine

4. Final conclusions, summary

For methane hazard assessment purposes of the "A" mine being abandoned, with consideration given to methane inflow from the longwalls abandoned during 2005-2017 time period located in numerous seams 612/2, 620/1-2, 620/1, 624, 626/2, 629/1, 629/2, 630/2, 703/1-2, 705/1, 705/2-3, 707/1-2, 708, 712/1-2, 713/1-2, 718/1-2, 720/1-2, 722/1-2 and 723, the method of computer simulation of ventilation process was used with application of the *VentGraph-Plus* computer program. Preparation of numerical model, adequate to the mine abandonment conditions and supplemented with data of methane inflow from extensive, post-mining goaf from the years 2005-2017, was important element of the program application.

The identification of methane emerging time at ground surface of the "A" mine being abandoned, and value of this methane concentration, were assumed as detailed purpose of the research. Two examples have been presented, differing from the preceding scenario, and obtained results are visualised in the graphical form of methane concentration changes in characteristic places of the "A" mine. The analysis and interpretation of the results for both examples show that:

1. Until the fan shut down on the Ryszard II shaft, methane concentrations in the mine excavations of the mine are at a safe level, well below 2%. This can be observed on the spatial diagram of the mine, and the mine excavations are depicted with a green bold line (Fig. 6). Only within area of goafs, increased methane concentrations are observed.

2. In the moment of fan shut down on the Ryszard II shaft, the volume of the air flowing through mine excavations of the mine lowers instantly, while the depression resulting from the air and methane transport and depression created by fans in the "R" mine, starts to significantly influence the flow of the air and methane mixture. This results in inverting directions of the air and methane flow in many mine excavations of the mine being abandoned. Fig. 7 presents changes of air volume flowing in the Ryszard II shaft, in the time period starting from fan shut down (July 2017) until the moment of the backfilling (November 2018) of the shafts and the construction of concrete slabs on the shafts. The final value of the air flow in the fan duct amounts to 14.2 m^3/min.

3. The fan shut down on the Ryszard II shaft results in an inversion of the air flow direction (Fig. 10) in the "R draining dip-mine excavation in the 713/1-2 seam" connecting both mines.

4. At the moment of shutting down fans on the "R" mine shafts, change of the air and methane mixture flow direction is observed; the mixture flows through the connection mine excavations to the "R draining dip-mine excavation in the 713/1-2 seam" of the "A" mine under abandonment (Fig. 10).

5. While observing changes of methane concentration in the Ryszard II shaft (Fig. 8), one can notice that its level is significant and reaches temporary values in the range of 6-7% CH_4. After completion of closure works (November 2018), methane concentration slowly decreases, to achieve 3.2% CH_4 after 4 years. For the purposes of methane concentration level checking, e.g. in sealed Ryszard II and Chrobry shafts, it is recommended to make an inspection borehole for monitoring the concentration of methane flowing out from the Ryszard II shaft.

6. The significant changes of methane concentration (Fig. 9) in the connection "R draining dip-mine excavation in the 713/1-2 seam" with the "R" mine are present because of the construction of gas-tight water dam, the depression effect of fans in the "R" mine and the near-by methane inflow from abandoned R-15 longwall. The concentration temporarily reaches 22% CH_4, and in further stages decreases, to reach 3.5% CH_4 after a four years lapse, and decreases slowly further.

7. It is found, while observing changes of methane concentration in the Ryszard II shaft following shutting down fans on the "R" shafts after 2 years (Fig. 8), that its level increases and reaches temporary values within 12% CH_4 range. It is observed, that after a 3 year lapse, the concentration slowly decreases, to reach a value below 9.0% CH_4, and decreases slowly further.

8. There is no methane emerging within area of abandoned Jedłownik shaft, resulting from the shutting down of fans on the Ryszard II shaft and the neighbouring "R" mine.
It results from a significant, in this time period, methane inflow from extensive goafs,

and also the influence of natural depression in the mine excavations of the Ryszard II and Chrobry I shaft bottoms, as well as sealed connection with the "R" mine.

9. To summarize the above, one can state, that there exists increased risk of emerging dangerous concentrations of methane on the surface. This is a long-term temporary condition, lasting many years. As methane exhalations from goaf decreases, the risk of methane emerging on the surface at significant concentration is falling.

The completed simulations of ventilation process during the closure of mine excavations and transfer of inflowing methane, indicate useful possibilities of computational tool used, which is the *VentGraph-Plus* computer program. However, it should be noted that in order to obtain proper results, it necessary to possess extensive knowledge and a database regarding both the structure of mine excavations, and the process and order of longwalls abandoning, as well as actions undertaken and abandonment works connected with sealing and backfilling of shafts.

Acknowledgments

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