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Numerical Simulation of Shearer Operation in a Longwall District

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Abstract: This paper presents a relatively simple method to analyze potential methane hazard and preventive methods based on a computer simulation of the airflow and methane emission on the longwall face and in the goaf. The presented approach considers the operation of a longwall shearer and conveyers and their possible impacts on both direct emissions of methane and migration from adjacent goafs. In this work, an attempt was made to control the advance speed of the virtual mining system based on sample mining data in the longwall 841A area and the abandoned longwall 841B at the Bielszowice Hard Coal Mine. The objective of this study was to verify the suitability of the adopted control algorithm. The results obtained from computer simulations of the mining operation with the developed control algorithm are presented in graphics of methane concentration, shearer advance speed and the speed control system parameters.

Keywords: mine ventilation; methane hazard in longwall; control of shearer operation; monitoring system

1. Introduction

Despite the trend of shifting to renewable energy sources, hard coal remains the primary energy source in many countries where its exploitation is often accompanied by the release of considerable amounts of methane. Some of that methane can be removed by the methane extraction system, yet the remainder is released into the atmosphere as a greenhouse gas. Therefore, it is important to investigate the potential for the reduction in the amount of methane discharged into the atmosphere with the amount coal production.

The development of modern technology has caused significant changes in the control of the longwall operations in modern mines, including remote control with operators at a safe distance from machines. Contemporary solutions developed by R&D teams from the world's leading shearer manufacturers, such as Eickhoff (www.eickhoff-bochum.de), Joy (www.mining.komatsu), and Caterpillar (www.caterpillar.com), have introduced effective control systems for maximizing output. Currently, algorithms for the automatic control of longwall complexes consider the mining and geological conditions, as well as the technical parameters, of applied devices and systems [1–3]. So far, these solutions have not helped to manage the methane hazard. Emergency power shutdown due to excessive methane levels as required by the safety regulations in most countries reduces the threat of explosion but results in huge losses due to work and time-consuming procedures to safely resume mining. Restoring safe conditions must be monitored not only at the longwall, but at all possible paths of its removal through the ventilation system. Eventually, a considerable amount of higher concentration methane reaches the atmosphere on the surface.

The issue of methane release into longwall headings during coal winning with the use of a shearer has been generally well-established and has been widely discussed in global publications [4–7].

In highly gaseous mines, methane frequently poses a significant constraint on the use of modern and highly effective longwall operations [2].

For these reasons, in mines with potential methane hazards, the manual control procedures use different methods of hazard prediction, such as linking the shearer operation with the continuous manual monitoring of the methane concentration in its surroundings. These necessitate the need to take into account the methane hazard in the shearer control algorithms. For some time, the shearers have been equipped with control systems implementing increasingly complex algorithms [1,3]. Therefore, they can be potentially supplemented with a pre-planned algorithm to address this issue.

The shearer cutting rate should be dictated by the highest concentration of methane in the longwall ventilating air stream, measured by the methane meters of the mine's gasometry system, and should not exceed the maximum emission value when power to the longwall is cut off. Eliminating the downtime caused by such shutdowns should result in an increased mining output.

The possibility to meet this goal was validated by a numerical simulation of the longwall shearer operation with an automatic methane concentration control system. This paper describes a longwall area model with an operating shearer and adjacent goafs, and presents a numerical simulation the results for the shearer operated with the feed speed control, depending on methane concentration in the airflow from the longwall (operation in automatic control mode), and for the shearer operated without the control.

2. Model of the Longwall Area in the VentGraph-Plus Software

To perform the numerical simulation of the longwall area with the shearer operating with and without the automatic feed speed control, the VentGraph software was used, with the models of goafs and the longwall area being cut by the shearer. The program is designed to simulate a fire in the mine and the distribution of fire gases in the mine ventilation system [8,9], as well as to simulate the methane distribution in the longwall system. The program uses the mesh method for solving the network, where the system of nonlinear mesh equations is solved with the Hardy Cross method [10]. The calculated air volume in the branches makes it possible to determine the air velocities, which in turn allow the displaying of the propagation of fire gases or methane in the mine's ventilation system. The system of equations describing the airflow in the ventilation branches and the gas propagation model is given in Part V. GRAS and Part VI. FIRE User's Guide Ventgraph for Windows [8] and in a number of publications [11–13]. The methane flow simulation program in the mine ventilation system was validated using the time series distance measure [14]. One series was the methane concentration curve recorded by the methane meter of the gasometry system every 1 min, and the second series was the recording of the virtual methane meter readings of the simulation software also with a 1-min interval. Comparisons of series were made for eight methane meters recording the concentration of methane after the discharge on 25 November 2005 in the D-6, seam 409/4 transport gallery at KWK "ZOFIÓWKA" mine, and for the same number of virtual methane meters in the program simulating the sample incident.

In the methane balance of the longwall area, it is necessary to take into account the methane flowing from adjacent goafs using the goaf model. The goafs are represented here by a grid of mutually perpendicular branches, and the aerodynamic resistances are derived from the filtration equations. The model described in [15,16], and [17,18] presents the results of the comparison of the methane concentration curves recorded by the methane meters of the gasometry system in the Bielszowice and Budryk mines to those obtained from the computer simulation using VentGraph.

Other sources of methane in a longwall being cut with a shearer include the emission from the body of coal of the longwall being mined and the output on the longwall and haulage conveyors. Such methane sources were included in the longwall model with the shearer and conveyors, as described in [19]. In order to describe the outflow of methane from a longwall face using a shearer at a specific point, the model assumes a linear increase in the rate of release as the shearer cutting at a constant rate approaches that point, and a linear decrease in the rate of methane release, when the shearer moves

away from that point. This is a linear approximation of the methane emission curves obtained through theoretical and experimental work by Tarasow and Kołmakow [20]. The volume flow of methane released from the unit length of the excavated material, exponentially decreasing with time [21], was adopted to describe the methane release from the excavated material on the conveyors.

The limitation of the model was the assumption of the shearer cutting at a constant rate without interruptions and in one direction. In practice, the shearer moves at a variable speed, dependent on the methane emission rate (among other factors). In addition, the shearer may have stoppages and may excavate bi-directionally, and if the power supply to the shearer is switched off, the conveyors may also be stopped. Therefore, the necessity arose to develop supplements to the model, allowing for such scenarios. The paper [22] presented an extended mathematical model of methane emissions from the body of coal being mined and supplemented the mathematical model of methane emissions from the armored face conveyor and belt conveyor. This model assumes a linear density distribution of the methane volume flow in the fracture zone of the longwall face in front of the shearer, and that the rate of methane emission from the newly exposed coal behind the shearer linearly decreases with time. Consequently, a space-time image of methane emission from the longwall is obtained, which is closely related to the shearer trajectory and the cutting schedule [23]. The methane emission model of the excavated material on conveyors, with exponentially decreasing methane volume flow per unit length of the excavated material, was extended based on the work of Airuni [24] and data in the work of Klebanov [25] and Kozłowski [26]. Instead of one time constant, in this model four different ones were introduced for the grain classes of the excavated material. These mathematical models provide a full description of the phenomena associated with methane emissions in a longwall cut using a shearer and form a mathematical model of the longwall. Such a longwall model with a shearer was used in the VentGraph-Plus simulation software with a given cutting schedule [23].

Another step in the development of the VentGraph-Plus simulation software was the addition of a shearer advance rate controller module in the feedback loop, where the controlled quantity is the concentration of methane in the air current flowing from the longwall face. A classical proportional–integral–derivative (PID) controller was used. The input here is methane concentration, measured by a virtual methane meter located in the ventilation system model at the longwall tailgate. The virtual methane meter models all functions of the methane meter in the system—i.e., in addition to measuring the methane concentration, it sends a signal to turn off the power supply to machines and devices in the longwall area when the methane concentration exceeds 2%. The difference of the measured value and the set methane concentration delivers an error signal to the output of the summation node. This signal is given to the inputs of the proportional (P), integral (I) and derivative (D) units of the controller. The amplification factor of the proportional module accounts for the amplifying of the signal error. The amplification factor of the differentiating module accounts for the amplifying of the derivative of the signal error, while the amplification factor of the integral element accounts for the amplifying of the integral of the signal error. The shearer advance rate calculated by the controller output system is proportional to the sum of the P + I + D signals. The controller module and the entire feedback loop of the automatic methane concentration control system by controlling the shearer rate are described more in detail in [27]. Dziurzyński, et al. [28] present a method of calculating the model parameters describing the emission of methane from a longwall being cut with a shearer on the basis of the methane concentration curves recorded by the three methane meters of the mine gasometry system.

For the simulation of air and methane flow in the longwall 841A and in the abandoned longwall 841B, as well as their goaf in the context of longwall mining performed with a shearer, a database was developed, containing the parameters of the mathematical model applied [23]. Data preparation can be divided into two stages: the data obtained from ventilation measurements, relating to the longwalls and excavations, and the data obtained by analyzing the mining and geological conditions and theoretical considerations [29]. Data for the longwall excavation and goaf areas include the following:

- Longwall ventilation system that determines the structure of the calculation area;
- Structure of excavations, at the beginning and end of the excavation;

- Determination of the goaf area and data related to the type of roof rocks, resistance to roof splitting, and height of the exploited longwall, as well as the panel length for the simulated example;
- Designed absolute methane release of longwall 841A from the exploited seam and seams located below or above;
- Length and cross-sectional area of the excavations;
- Elevations of longwall excavation nodes and goaf areas;
- Aerodynamic resistance of excavations in the area (e.g., longwall, main, headgate and tailgate);
- Air densities in individual excavations.

Based on the above data, the structure of the excavation and goaf network was determined (Figure 1), which reproduced the actual structure of the excavations and goafs and the ventilation system.

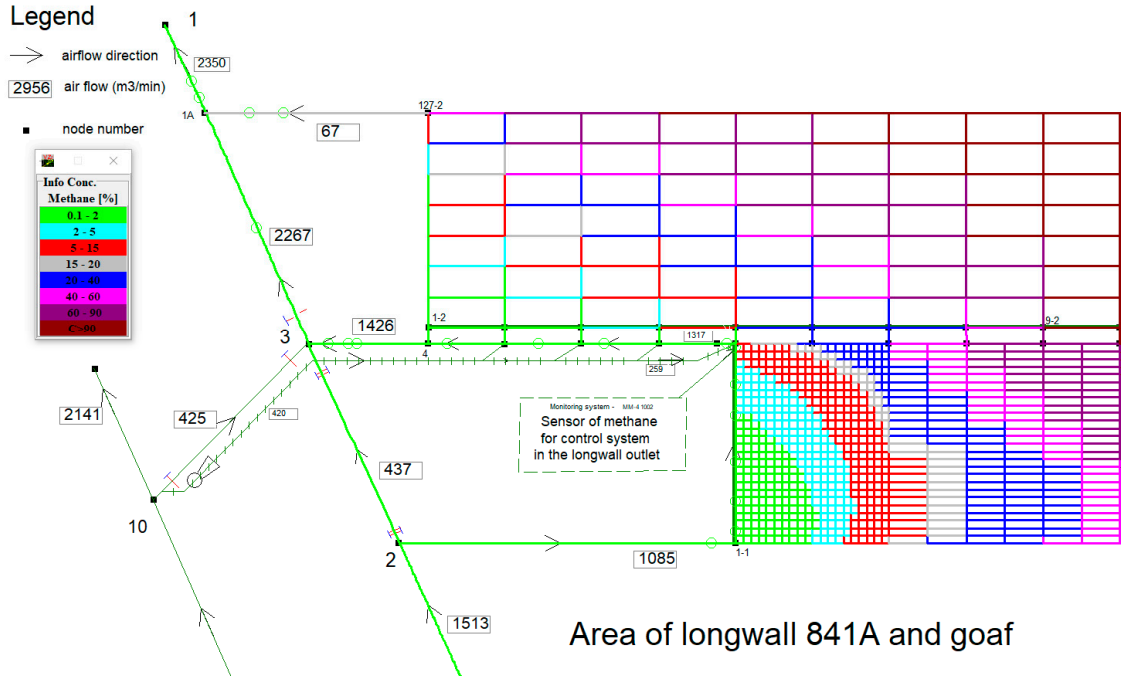


Figure 1. A ventilation scheme of the longwall 841A district with grids of goaf branches. Rectangles show the airflow volume stream (m^3/min); arrows show the direction of flow. Numbers at junctions highlight their identification.

To determine the data characterizing the airflow in the goafs, the theoretical model of the permeability distribution and formation of goaf heights [29,30] was used, together with the data resulting from the analysis of the seam map, geological profiles, and longwall mining plan. Using the above-mentioned data, parameters characterizing the goaf area were determined: permeability for longwall 841A changes exponentially from 9×10^{-8} (for 50 m of longwall panel) to 3.5×10^{-9} m^2 at the place where longwall mining starts (550 m) and porosity from 0.5 to 0.2%, respectively. Permeability for abandoned longwall 841B changes from 8×10^{-8} m^2 at the place where mining ends to 3.5×10^{-9} m^2 at the place where longwall mining starts (850 m), and the porosity is from 0.5 to 0.2%, respectively. The adopted values of permeability and porosity distribution were chosen in the validation process of the numerical model of longwall 841A and the 841B area and the results are presented in paper [18].

To determine the initial airflow and methane mixture for the numerical model of the longwall, longwall excavations, and goafs—data recorded by methane concentration sensors and stationary anemometers of the monitoring system—were used.

Recordings of methane concentration change before and during mining with the shearer of longwall 841A and abandoned longwall 841B, as well as their respective goaf, allowed us to determine

the methane in airflow on longwall faces and in the tailgate and headgate from the longwall and the methane flowing into the goaf area.

The longwall 841A, a mined system with caving, with "U"-type ventilation along the body of coal, was 130-m long, with an average longwall height of 2.9 m, cross-section 8.2 m^2 and a panel length of 550 m. The depth was in the range of −732–899 m. The surface fan for the longwall district had 3200 [Pa] pressure and an airflow of 12,800 m^3/min. This ventilation system was constant during simulation.

The longwall was mined with a shearer (longwall-type KSW-475W/2BPH), with a web of 0.75–0.8 m, and the initial speed of shearer advance during cutting was 2.0 m/min. Haulage from the longwall uses an armored face conveyor Patentus-PAT E260 and Grot = 750/S at a speed of 1.33 m/s. Additionally, a belt conveyor at a speed of up to 2.0 m/s was used. The area of longwall 841A bed 405/2 was characterized by an inflow of 39.66 m^3CH_4/min. An average of 42% effectiveness of methane drainage was estimated in the technical design of the longwall. Due to the gas hazard, the designed mining output was limited to 2600 tons/day. The amount of air in the headgate to the longwall was 1085 m^3/min. The longwall tailgate corner was supplied with fresh air (259 m^3/min) through an air duct delivering the air to the remaining section of the gate and was liquidated behind the face line. The flow at the tailgate return was 1426 m^3/min. This discrepancy of the air balance is due to the fact that, during the excavation, air was discharged from the longwall due to a leaky duct in the excavation. Daily winning of the longwall was planned in accordance with the relevant Polish mining regulations [31], based on the designed total methane release, assumed output, and prevailing ventilation conditions. This estimate was made regarding the value of so-called criterial methane release and a comparison was then made with the assumed methane release (criterial methane release is total methane release for which, in regular conditions of ventilation and drainage and with uneven methane release, the admissible methane concentration in the return air stream is not exceeded). Table 1 lists design and assumed values of methane and air flows.

Table 1. Determination of the methane release for longwall 841A.

No.	Ventilation and Methane Inflow Parameters	Unit	Value
1	Methane inflow stream provided with fresh air current	(m^3/min)	3.00
2	Designed absolute methane release of longwall 841A (sum no. = 4 + 5 + 7)	(m^3/min)	39.66
4	Average methane intake by methane drainage	(m^3/min)	11.16
5	Methane inflow to goafs 841A	(m^3/min)	15.40
6	Methane inflow to goafs 841B	(m^3/min)	2.80
7	Methane inflow from the face of the longwall and the mined coal seam	(m^3/min)	13.10
7	Airflow at longwall	(m^3/min)	1085
8	Air duct flow	(m^3/min)	259
9	Criterial methane release with drainage	(m^3/min)	21.6
11	Ventilation methane release	(m^3/min)	20.9

Based on the above data and the applicable mining regulations, the following parameters of the automatic methane measurement and control system were used:

For methanometry:

- Methane concentration level for switching power off—adopted parameter 2.0% CH_4;
- Methane concentration level for switching power on—adopted parameter 1.8% CH_4;
- Time of delay in switching power on (min)—adopted parameter 1 min.

For the controller in the calculating circuit:

- Planned value of the methane concentration—adopted parameter 1.5% CH_4;
- Amplification factor of the proportional module—adopted parameter 600;
- Amplification factor of the differentiating module—adopted parameter 1200;

- Amplification factor of the integral module—adopted parameter 0.0;
- Time for calculating the speed of changes to the methane concentration (min)—adopted parameter 10 min.

Figure 2 shows the VentGraph-Plus program dialog box for data input for the automatic methane concentration control system.

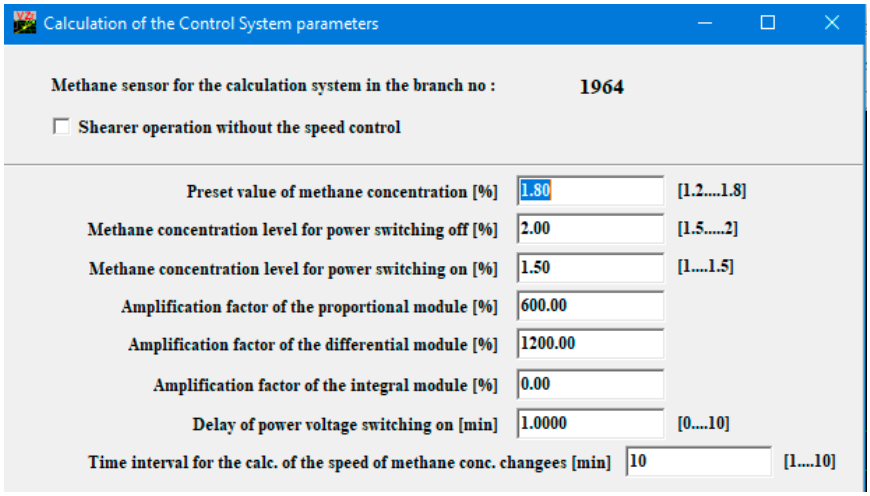


Figure 2. Parameters of automatic methanometry and the calculating circuit.

Figure 3 presents the dialog box of the adopted parameters for a model of methane emissions arising from the longwall shearer mining and haulage by conveyors [27,28]. The data presented in Figure 3 may be divided into three main groups.

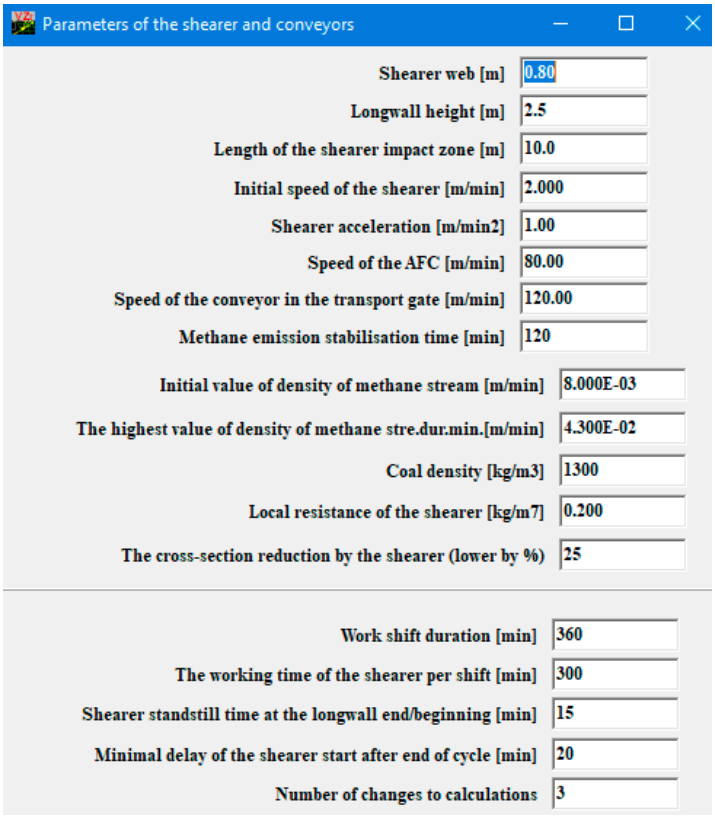


Figure 3. Adopted parameters of a model of methane emissions.

The first one contains the parameters of longwall characteristics, which should take into consideration the value of local moving aerodynamic resistance arising from the presence of the shearer, longwall mining height, coal density, web size, initial mining speed of the shearer, acceleration of the shearer, speed on the face conveyor and panel belt conveyor in the maingate.

The second group of data consists of model parameters concerning methane emissions from the mined coal transported with conveyors:

- Length of the impact zone of the shearer (zone of methane emissions) (m);
- Stabilization time of emission release from the face during operation (min);
- Initial rate of methane release (m/min);
- Highest rate of methane release (m/min);

The work of [32,33] includes a great deal of valuable data pertaining to the release of methane during mining and haulage on conveyors.

The third group of data is comprised of parameters specified in the schedule of the total shearer operating time—i.e., during the shift, the operation time of the cutter-loader, idle time of a shearer at the end or the beginning of the longwall (change of mining direction), idle time of the shearer after the end of the shift, and limitation of the time of the start of the shearer after the cycle ends. This limitation blocks the start of the shearer after being idle at the beginning or end of the longwall, when less time remains until the end of the shift than the pre-set value.

3. Numerical Simulation Results

An example of the shearer operation in longwall 841A and the haulage was considered. Due to methane hazard, three consecutive 6-h mining shifts (18 h per day) were adopted for the calculation. The operating time of the shearer was assumed to be 330 min during a shift. The total idle time of the shearer during a preparation for the next mining cycle was 15 min. The delay of starting the shearer at the beginning or end of a shift was 20 min.

Example

To verify the effects of mining speed control, calculations were made for the above described data for two cases: a controlled case (intermittent orange line), and a second case with a constant mining speed—i.e., without the intervention of the control system (black line) (Figure 4).

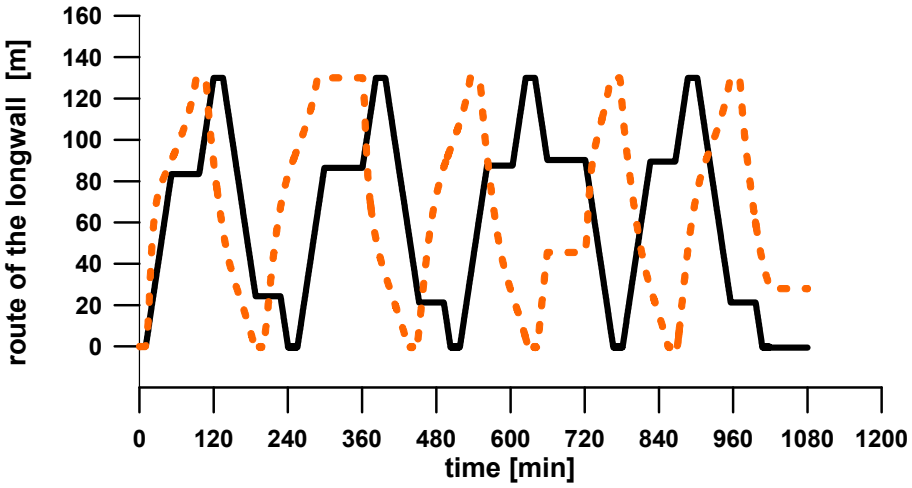


Figure 4. Route of the shearer in longwall 841A, where the intermittent orange line represents the controlled speed and the black line indicates the case without speed control.

The results of the virtual mining set (shearer and conveyors for haulage of winning) in longwall 841A are presented in subsequent figures. The diagram in Figure 4 shows the route of the shearer in

longwall 841A for the adopted control parameters (Figure 2), with the continuous black line (Figure 4) representing the mining speed for the constant speed of 2 m/min.

Figure 5 shows the shearer cutting, where the continuous black line represents the shearer speed for a constant 2 m/min speed and the intermittent orange line indicates a controlled speed.

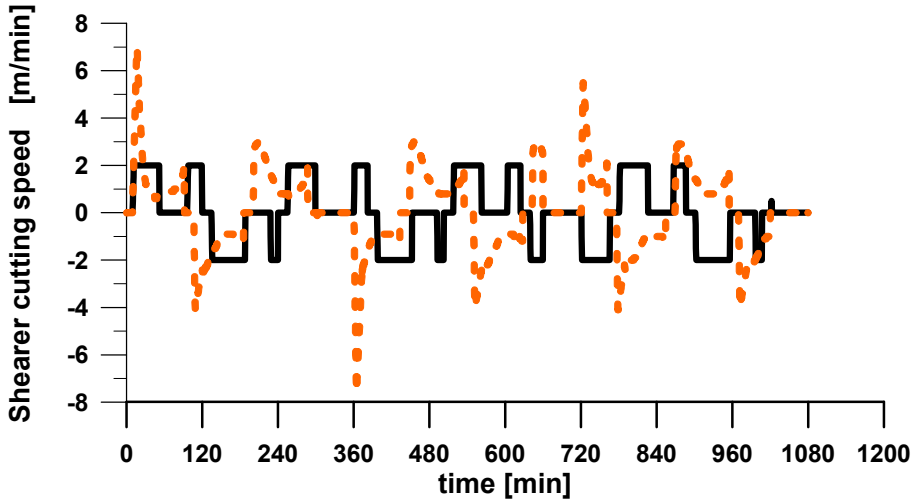


Figure 5. Shearer cutting speed in longwall 841A, where the intermittent orange line represents the controlled speed and the black line indicates a case without speed control.

By observing Figures 4 and 5, the shearer operation route and speed with a system of automated shearer speed regulation and without regulation can be compared. The presented graphs facilitate the understanding of the regulation system's operation and show changes in the shearer cutting speed.

Figure 6 shows the mining output for the two cases simulated. Greater winning was recorded during the controlled operation, as shown by the intermittent orange line.

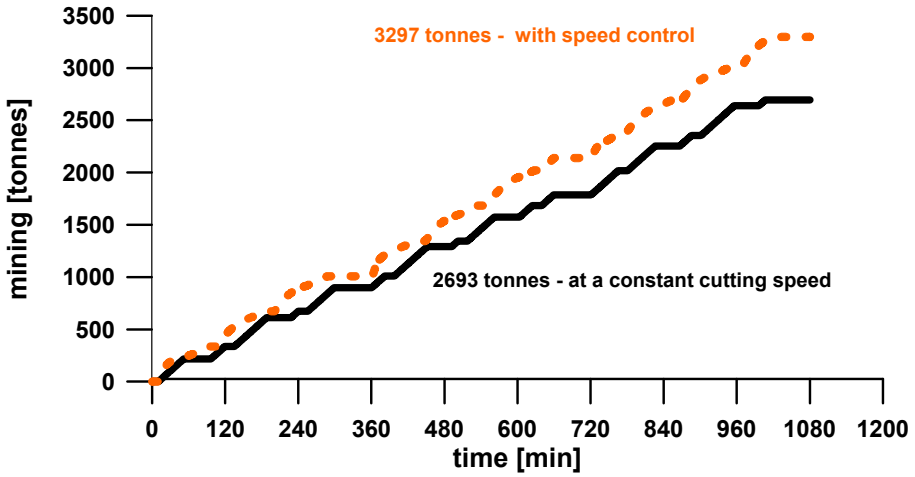


Figure 6. Mining output (tons), where the intermittent orange line represents a case with speed control (3062 (tons)) and the black line indicates a case without speed control (2683 (tons)).

Figure 7 shows changes in the methane concentration for a sensor situated at the end of the longwall. According to the assumptions, the air curtain methane is mixed with the supplied air in the tailgate.

Without the control system (black curve), whenever methane concentration exceeds 2%, power will be automatically cut off and the shearer stops until the methane concentration falls below 1.5%.

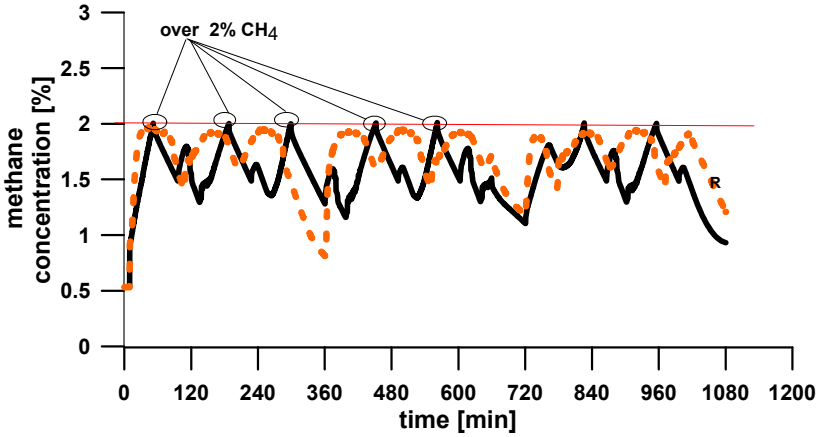


Figure 7. Changes in the methane concentration measured using a virtual sensor situated on the end of longwall, where the intermittent orange line represents a case with speed control and the black line indicates a case without speed control.

If the control system is activated (intermittent orange curve), this reduces the mining speed in advance, lowering methane emissions during mining, and does not permit the admissible methane concentration to be exceeded.

The figures below show changes in the methane concentration measured by virtual sensors situated at 115 m in longwall 841A (Figure 8) and the end of the tailgate (Figure 9).

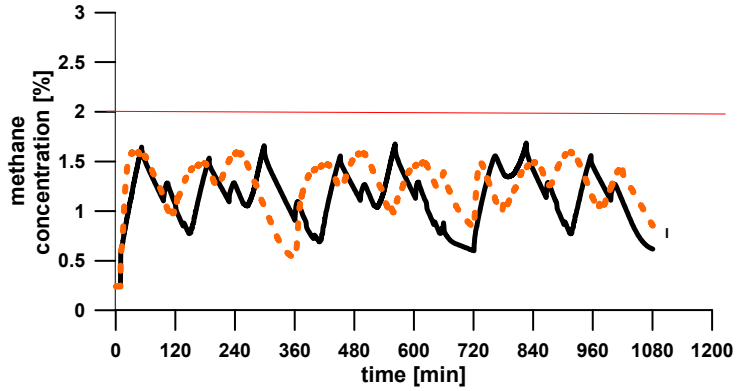


Figure 8. Changes in the methane concentration measured by a detector in the longwall at 115 m, where the intermittent orange line represents a case with speed control and the black line indicates a case without speed control.

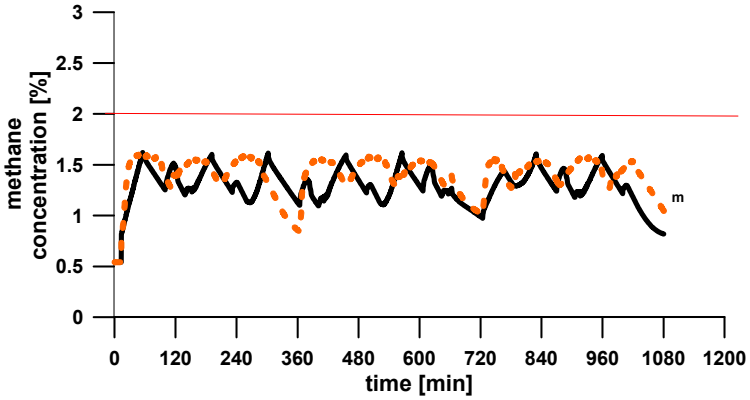


Figure 9. Changes in the methane concentration in terms of the end of the tailgate, where the intermittent orange line represents a case with speed control and the black line indicates a case without speed control.

4. Discussions

Mining processes and physical movement of the shearer operation in a gassy environment are not sufficiently understood. Therefore, the issue is far from being resolved with the simple technical implementation of known solutions. In previous publications [19,23,29], the authors proposed models describing the state of regional ventilation in longwall mining using a shearer [27]. They were implemented in the Ventgraph-Plus program. The functions of the program were also extended to represent the control system. Therefore, a research tool was developed, using a computer simulation method to establish the relationship between the operation of the control system and the methane hazard level. The Ventgraph-Plus program enables the effectiveness of the proposed control method to be forecasted.

The quality of forecasting results depends on the quality of input data and model building. It was initially made on the basis of the compliance of simulation results with historical data from the selected site. Airflow and gas concentration measurements are being conducted at several longwalls. The results of the measurements will provide data for a more accurate validation of the methane propagation model in the longwall using a shearer. The obtained measurement results will allow for the validation of the simulation, taking into account the operation of the shearer and the automatic regulation system. In particular, this will allow for a better location to be selected for a methane sensor that would be useful for the control system and relevant to the control performance.

The interaction between air and methane flows is too complex to lend itself to easy predictions of the effectiveness of individual solution. Using empirical case for a solution in a site operated in potentially explosive atmospheres is too risky. The proposed simulation provides a chance to provide a preliminary attempt to solve the problem. Once satisfactory results are achieved, testing the control system in real conditions may be considered.

The objective of this study was to determine the possibilities of controlling longwall shearer operation—in particular, its speed with an automatic PID-type controller. The obtained results indicate that it is possible to control the speed of a shearer and may result in increased coal production (Figure 6). The use of the controller made it possible to achieve higher production with a simultaneous control of methane release to the atmosphere. Figure 10 shows the methane volume flow per unit of coal production generated with a shearer with and without the controller of the shearer feed rate.

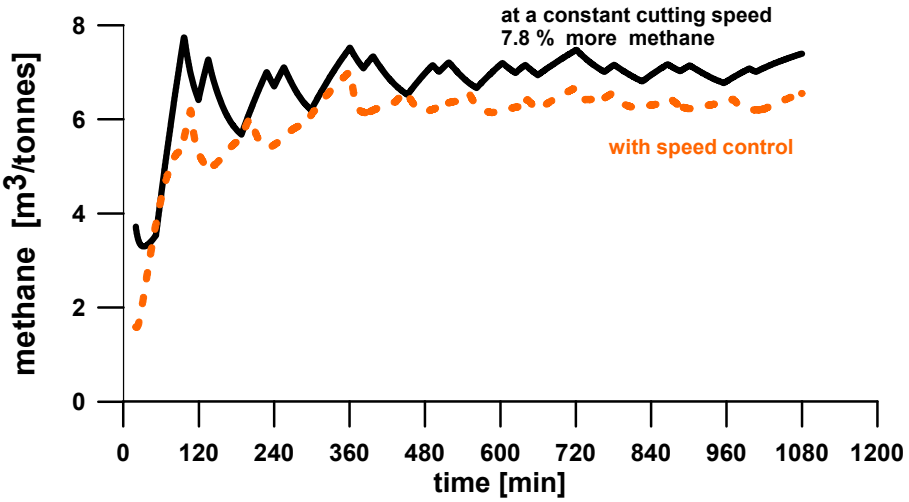


Figure 10. Changes in the methane volume flow per unit of production in the end of the tailgate where the intermittent orange line represents a case with speed control and the black line indicates a case without speed control.

The simulations and calculations indicated that 7.8% less methane flows into the ventilation paths when the shearer controller is used, assuming the same coal production. For the example considered,

1683 m^3 less methane is released into the atmosphere per day, which is beneficial for reducing the greenhouse effect.

It is recommended that further research be conducted in order to:

- Determine the optimum settings of the controller parameters for specific mining and geological conditions;
- Determine the recommended locations of methane detectors in the area of the longwall, which would be used to supply data to the control system;
- Determine the technical potential of using a longwall shearer in conditions of a controlled mining speed;
- Continue studies, both experimental and numerical, to establish a database for validation of the modified numerical model for the operation of the shearer speed control system [34,35];
- Continue to optimize mathematical models using VentGraph-Plus—e.g., with a specific methane emission occurring when when the hydraulic roof supports advance behind the operating shearer.

The results presented in the current paper show the potential of the proposed control system in longwall mining. Such a system will be a fully innovative approach to the automation of the longwall operation in conditions of a significant methane hazard aimed at increasing both the productivity and safety by lowering the number of emergency stoppages, reducing manpower on the longwall face and reducing the negative environmental impact of the uncontrolled release of methane from coal mines.

Author Contributions: W.D. provided a general idea and test simulations; A.K. customized and benchmarked the control system; T.P. developed, tested, and described the software; W.D., A.K., and J.K. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Peng, S.S.; Du, F.; Cheng, J.; Li, Y. Automation in U.S. longwall coal mining: A state-of-the-art. *Rev. Int. J. Min. Sci. Technol.* **2019**, *29*, 151–159. [CrossRef]
2. Jaszczuk, M. *Integrated Control of the Technological System Longwall Face-Loading Point*, 1st ed.; KOMAG: Katowice, Poland, 2008; pp. 3–7. ISBN 9788360708224. (In Polish)
3. Fiscor, S. Improved safety and productivity through advanced shearer automation. *Coal Age* **2017**, *122*, 16–23.
4. Brune, J.F.; Saki, S.A. Prevention of gob ignitions and explosions in longwall mining using dynamic seals. *Int. J. Min. Sci. Technol.* **2017**, *27*, 999–1003. [CrossRef]
5. Schatzel, J.; Dougherty, H.; Krog, R.B. Methane emissions and airflow patterns on a longwall face: Potential influences from longwall gob permeability distributions on a bleederless longwall. *Trans. Soc. Min. Metall. Explor. Inc.* **2017**, *342*, 51–61. [CrossRef]
6. Schatzel, J.; Karacan, C.O.; Krog, R.B.; Esterhuizen, G.S.; Goodman, V.R. *Guidelines for the Prediction and Control of Methane Emissions on Longwalls*; Circular 9502; Department of Health and Human Services, National Institute for Occupational Safety and Hazard: Pittsburgh, PA, USA, 2008.
7. Zapletal, P.; Prokop, P.; Štemberka, M.; Gibesová, B.; Vavříková, E.; Trčková, H. The calculation of methane concentration emitted from the coal face. *Arch. Min. Sci.* **2016**, *61*, 83–93. [CrossRef]
8. Dziurzyński, W.; Pałka, T.; Krawczyk, J. *Ventgraph for Windows—Ventilation Engineer's Program System for Analyzing the Ventilation Network under Normal and Emergency Conditions—Simulation of Transient Flow of Air and Fire Gases*; Transaction of Strata Mechanics Research Institute: Krakow, Poland, 2013; pp. 7–100. ISSN 1509-2593.
9. Pritchard, C.J. Validation of the Ventgraph program for use in metal/non-metal mines. In Proceedings of the 13th US/North American Mine Ventilation Symposium, Sudbury, ON, Canada, 13–16 June 2010; pp. 455–462.
10. Cross, H. *Analysis of Flow in Networks of Conduits or Conductors*; BULLETIN No. 286; Engineering Experiment Station, University of Illinois: Urbana, IL, USA, 1936; pp. 5–38.

11. Litwiniszyn, J. Gas Emission from a Crushed Rock Medium during its Sudden Outburst. *Arch. Min. Sci.* **1987**, *32*, 155–168.
12. Krach, A. Node method for solving the mine ventilation networks. *Arch. Min. Sci.* **2011**, *56*, 601–620.
13. Dziurzyński, W.; Tracz, J.; Trutwin, W. About the mathematical model of air and blast gas flow in a mine ventilation network. *Arch. Min. Sci.* **1987**, *32*, 3–10. (In Polish)
14. Dziurzyński, W.; Krach, A.; Krawczyk, J.; Pałka, T. Application of the distance factor of time series for the validation of the mine ventilation mathematical model applied in the VentMet programme. *Min. Rev.* **2007**, *63*, 28–33. (In Polish)
15. Dziurzyński, W. Numerical Simulation of the Ventilation Process of the Mine's Ventilation Network; Monographs Series 2. Ph.D. Thesis, Transaction of Strata Mechanics Research Institute, Krakow, Poland, 2002.
16. Nawrat, S.T. Experimental and model investigations of the process of filling with methane headings with brattices and stoppings in hard coal mines. *Sci. Res. Implement. Stud.* **1999**, *1*, 146–186. (In Polish)
17. Dziurzyński, W.; Krach, A.; Pałka, T.; Wasilewski, S. Validation of the computer ventilation simulation program VentMet for the longwall area, taking into account the time-varying methane sources associated with the shearer's cyclic operation. *Trans. Strata Mech. Res. Inst.* **2007**, *9*, 3–26. (In Polish)
18. Dziurzyński, W.; Krach, A.; Pałka, T.; Wasilewski, S. Digital simulation of the gas dynamic phenomena caused by bounce, experiment and validation. *Arch. Min. Sci.* **2010**, *55*, 403–425.
19. Blecharz, B.; Dziurzyński, W.; Krach, A.; Pałka, T. Simulation of air and methane mixture flow at longwall area regarding coal getting and haulage process. *Mech. Automat. Min.* **2003**, *3–4*, 55–67. (In Polish)
20. Tarasov, B.G.; Kolmakov, W.A. *Coal Mine Gas Barrier*; Niedra: Moscow, Russia, 1978; pp. 63–79. (In Russian)
21. Drzęźla, B.; Badura, H. Approximate distribution of methane concentration emitted from the excavated material. *Arch. Min.* **1980**, *25*, 249–260. (In Polish)
22. Dziurzyński, W.; Krach, A.; Pałka, T.; Wasilewski, S. Validation of the VentZroby program with the use of the results of the in situ experiment and with the use of new algorithms for the preparation of input data. *Trans. Strata Mech. Res. Inst.* **2008**, *10*, 67–102. (In Polish)
23. Dziurzyński, W.; Krach, A.; Pałka, T.; Wasilewski, S. Validation of computer simulation of air parameters at a longwall vs. results of an in situ experiment. In Proceedings of the 13th US/North American Mine Ventilation Symposium, Sudbury, ON, Canada, 13–16 June 2010; pp. 407–414.
24. Airuni, A.T. *Prediction and Prevention of Gas-Dynamic Phenomena in Coal Mines*; Nauka: Moscow, Russia, 1987; pp. 189–223. (In Russian)
25. Klebanow, F.S. *Aerodynamic Control of Gas Regime in Mine Ventilation Networks*; Nauka: Moscow, Russia, 1974; pp. 10–33. (In Russian)
26. Kozłowski, B. *Forecasting Methane Hazard in Hard Coal Mines*; Śląsk: Katowice, Poland, 1972; pp. 40–43. (In Polish)
27. Dziurzyński, W.; Krach, A.; Pałka, T. Shearer control algorithm and identification of control parameters. *Arch. Min. Sci.* **2018**, *3*, 537–552. [CrossRef]
28. Dziurzyński, W.; Krach, A.; Pałka, T.; Wasilewski, S. Methodology for determining methane distribution in a longwall district. *Arch. Min. Sci.* **2019**, *64*, 467–485. [CrossRef]
29. Dziurzyński, W. *Forecasting of the Underground Mine Ventilation Process under Underground Fire Conditions*; Studies, Dissertations, Monographs. No. 56; Mineral and Energy Economy Research Institute of Polish Academy of Sciences: Krakow, Poland, 1998; pp. 60–80. ISSN 0860-74-19. (In Polish)
30. Szlązak, J. *Methods for Calculating Air Flow and Methane Concentration Distribution in Goafs of Caving Walls, Examples of Use*; Publishing House of the Silesian University of Technology: Gliwice, Poland, 2010; pp. 3–134. (In Polish)
31. Krause, E.; Łukowicz, K. Rules for longwall mining in conditions of methane hazard. *Instr. Cent. Min. Inst.* **2004**, *17*, 2–16.
32. Godyń, K.; Dutka, G. The impact of the degree of coalification on the sorption capacity of coals from the Zofiówka monocline. *Arch. Min. Sci.* **2018**, *63*, 727–746. [CrossRef]
33. Kudasik, M.; Murzyn, T.; Skoczylas, N.; Wierzbicki, M. Methane emission model derived from hard coal during longwall excavation. *Trans. Strata Mech. Res. Inst.* **2015**, *17*, 107–114.
34. Gao, K.; Lijun Deng, L.; Liu, J.; Wen, L.; Wong, D.; Liu, Z. Study on mine ventilation resistance coefficient inversion based on genetic algorithm. *Arch. Min. Sci.* **2018**, *63*, 813–826. [CrossRef]

35. Wasilewski, S.; Branny, M. A preliminary study of the unsteady states of the ventilation parameters at the longwall face during the shearer operation. In Proceedings of the 12th US/North American Mine Ventilation Symposium, Reno, NV, USA, 9–11 June 2008; pp. 107–114.

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