Studying the Impact of the Location of Air-Duct Lines on Methane Distribution and Concentration in Dog Headings

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One of the basic issues associated with underground mining is providing a safe atmosphere in mine workings. This includes its chemical composition and reduction of hazardous concentrations of harmful gases. In particular, this applies to driven dog headings that have a one-sided connection to the central ventilation system in the mine. Therefore, it is necessary to use special ventilation systems in these areas. The widespread current methane hazard present in mine workings additionally increases the requirements of these systems. For this reason, the following paper presents the methodology and results of studies that looked at the ventilation system of driven dog headings. The aim of the study was to determine the impact of the location of air-duct lines on methane distribution and concentration in driven dog headings. The basis for the analysis were model studies carried out for the real system and for three additional location variants of air-duct lines forcing fresh air. The studies were carried out for the same real parameters of the air stream and methane emission in the studied dog heading. The results clearly show that the location of studied air-duct lines has an impact on the distribution and concentration of methane in individual points of the driven dog heading. The study also included the fracture zone as a porous centre around the driven dog heading, which enabled more accurate mapping of real conditions. The results broaden knowledge in the field of ventilation issues and should be used in practice.

Keywords: *underground coal mine, methane hazard, dog heading, ventilation, CFD.*

Introduction

An effective ventilation system is essential to ensure a safe and efficient process of underground exploitation of raw materials, including hard coal (Biały, 2013; 2014; 2018, Biały and Fries, 2019; Brodny et al., 2017; Brodny and Tutak, 2019). The main task of this system is to provide the right amount of fresh air, with a specific oxygen content, in the area of mining works, and thus ensuring the appropriate status (composition) of the mine atmosphere (Kurnia et al., 2016; Roghanchi et al., 2016; Tutak and Brodny, 2018; Tutak, 2020; Xiu et al., 2019; Cernecky et al., 2015). This condition should allow miners for free work and prevent the occurrence of dangerous concentrations of methane and other hazardous gases (Ordinance of the Minister of Energy, 2016). These requirements apply to all mine workings. However, for the workings of different specificity, the use of various ventilation systems is needed.

This mainly concerns dog headings driven in coal or gangue, which belong to the so-called "blind" or unidirectional mine workings. In other words, they have only one connection to the central (general) ventilation system of the mine (Brodny and Tutak, 2015). This, in turn, means that both fresh and used air is transported through the same heading (Brodny, 2010; 2011; 2012; Baranov et al., 2017). Fresh air must be supplied to the face zone, where the process of mining the rock mass is carried out, in such a way that it impedes neither the outflow of used air from this zone nor gases entering this heading from the rock mass. Due to their specificity, these headings require the use of a dedicated ventilation method.

For this purpose, the most commonly used method involves the so-called forced air-duct ventilation system, which consists of supplying fresh air to the face of a given dog heading. Through the face zone, this air flows all the way through the entire dog heading to later connect to the stream of used air from other headings and the mine's main ventilation network. A diagram of forced ventilation for the studied driven dog heading with the use of air-duct lines is shown in Figure 1.

This diagram also points to the fracture zone created during mining works (Małkowski et al., 2017; Masny et al., 2017; Prusek and Walentek, 2005; Prusek, 2008; Yang et al., 2019), which has a significant influence on the ventilation process.

In addition to ensuring an adequate composition of air in a dog heading necessary for miners to work in, the ventilation system must not allow for the exceedance of the permissible concentration levels of hazardous gases (Brodny et al., 2018, Krause, 2015; Tutak and Brodny, 2018). Methane is the most dangerous gas present during underground mining works, especially in coal (Zhao et al., 2019). Due to its flammable and explosive properties, methane is a huge threat to both safety and continuity of the mining process. Dog headings driven in coal are particularly vulnerable to the occurrence of hazardous methane concentrations. Methane is released into these dog headings from mined coal and exposed unmined coal as well as cracked ceilings, thills and side walls (Fig 1). Since this gas has a lower density than air, it usually accumulates in the ceiling zone of dog headings and in

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areas where the air supply is obstructed. They are referred to as dead zones. However, the phenomenon of methane accumulation in the ceilings is called methane layering (McPherson, 1993).

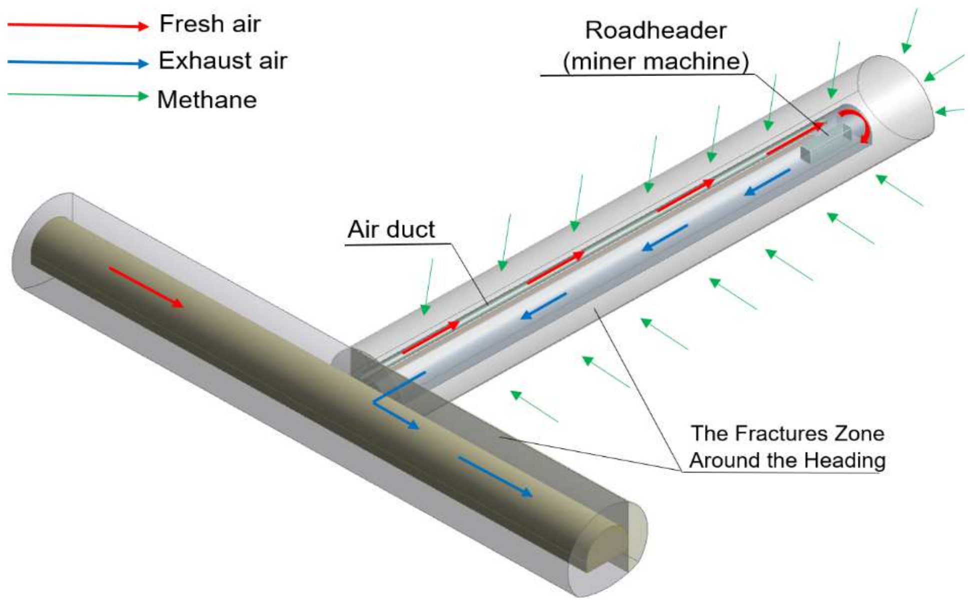

Fig. 1. A scheme of the excavated dog heading

In order to prevent the dangerous accumulation of methane and ensure an adequate atmosphere composition in driven dog headings, it is crucial to adapt the ventilation system and its parameters to the conditions in which mining works are performed. Therefore, the parameters of supplied air are selected depending on the geometry of driven dog headings, temperature and expected amount of methane released.

In addition to the parameters of supplied air, it is also important to properly locate air-duct lines supplying fresh air to dog headings. This mainly concerns headings into which large amounts of methane are released. The location of air-duct lines can affect the distribution of methane concentration in a given dog heading. Therefore, it is reasonable to determine what effect the location of air-duct lines supplying fresh air to a particular heading has on the distribution of methane concentration levels.

Literature on the ventilation systems in dog headings shows deficiencies in this respect although the subject area related to the study of airflows and mixtures of air and methane through dog headings has been presented in many papers (Kurnia et al., 2014a; Kurnia et al., 2014b; Sasimoto et al., 2013).

These papers, like many others, most frequently assumed that methane is released into dog headings from a given point, or from a surface, and only from the face area.

The analysis of literature proves that so far, there have been no studies which would determine the impact of the location of air-duct lines in dog headings on the distribution and concentration of methane. It was therefore assumed that from a scientific and practical point of view, this issue is relevant, and it is reasonable to conduct research in this area.

Therefore, in order to determine the impact of the location of air-duct lines on the distribution and concentration of methane in driven dog headings, model studies were performed in which the actual dog heading was mapped.

In the first stage of model studies, the actual ventilation system that was used in this dog heading was mapped (air-duct lines were located along the ceiling in the heading axis). This helped to establish the distribution of methane concentration. In order to assess the quality of the developed model, the findings were compared with the measurement results. A satisfactory correlation of these results (at three measuring points) enabled the analyses for additional three location variants of air-duct lines in the same heading. In total, four location variants of air-duct lines were analysed. The tests were carried out using numerical fluid mechanics (Kalentev et al. 2017). The calculations were made in the ANSYS Fluent program, based on the Finite Volume Method (FVM).

Due to significant difficulties in conducting studies in real conditions, the use of model studies seems fully justified in this case. The numerical method utilised for calculations enabled very accurate (for good mapping of geometry and reliable boundary conditions) determination of studied parameters, practically at every point of the studied area.

It should be emphasised that the study included the fracture zone around the dog heading. The size of this zone depends on many mining and geological factors. Its size was established based on the research presented in the literature on rock mass mechanics. It was also assumed that this zone is a porous medium with defined permeability, which was determined using the results of strength tests of the rocks in which the dog heading was being driven. Undoubtedly, this is a new, unused so far approach, which more accurately reflects the real conditions that occur in the rock mass affected by mining activity.

The paper presents the applied methodology, obtained results, discussion and final conclusions.

Materials and Methods

The flow of air in the mine heading was analysed by means of the Finite Volume Method (FVM). This method involves discretisation (in physical space) of the computational domain (the spatial flow area) into a finite number of non-overlapping control volumes. A control volume may be created, depending on the research tool applied, inside the volume of the fluid element or around the volume element node.

The tests were conducted for a spatial model of the area under analysis, using CFD. The authors' experiences and the results presented by other researchers indicate that this method is widely applied for analysing phenomena related to the flows of fluids and dust, the transfer of mass and heat or the processes of combustion (Veersteg and Malalasekera, 2007).

The paper made use of the ANSYS Fluent software (Ansys, 2011), which is one of the most popular tools for the CFD method, whereas the discretisation process was carried out by means of the FVM. The methodology for conducting studies by means of this program encompasses the development of a mathematical model of the phenomenon in question, the adoption of boundary conditions, the performance of calculations, and the analysis of the results.

Mathematical models

The flow of the air and methane mixture is described by the conservation equations for mass, momentum, energy and species transport. The conservation equations for mass, momentum and energy can be expressed as (Kurnia et al., 2014a, 2014b; 2016; Sasmito et al., 2013; Zhou et al., 2017):

$$\nabla \cdot U = 0 \tag{1}$$

$$\rho\left(\frac{\partial U}{\partial t} + U \cdot \nabla U\right) = -\nabla p + \mu \nabla^2 U + F \tag{2}$$

$$\rho\left(\frac{\partial E}{\partial t} + E \cdot \nabla E\right) = k \nabla^2 T + W_s + S_E \tag{3}$$

where: ∇ is the divergence operator, ρ is the air density (kg/m^3), U is the air velocity vector (where $U=u_x, u_y, u_z$) (m/s), t is time (s), ∇p is pressure gradient (Pa), μ is the dynamic viscosity (Pa·s), F is the body force vector (where: $F=F_x, F_y, F_z$), E is energy (J), k is the coefficient of conductivity (W/(m·K)), T is the temperature (K), W_s is the work done by surface stress (J), and S_E is the source term energy (J).

The basis of the mathematical description of the transport process of the methane emission to the driven dog headings is a mass conservation principle related to this gas. Mathematical model of the transport, being a system of equations of advection-diffusion, which for the i-th substance it takes the following form (Ansys, 2011):

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho U Y_i) = -\nabla \cdot J_i + R_i + S_i \tag{4}$$

where: Y_i means the local mass fraction of each species, J_i is the diffusion flux of species i (kg/(m^{2}s)), R_i means the net rate of production of species i by chemical reaction and S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources.

The flow of air-methane mixture through driven dog heading has turbulent character, in which there is an irregular movement of air molecules, and the parameters of its flow experience unpredictable random changes in space and time (Tuliszka–Sznitko, 2011).

Large Eddy Simulation (LES), Direct Numerical Simulation (DNS) and Reynold-Averaged Navier-Stokes (RANS) were used to describe turbulent flows (Fig. 2).

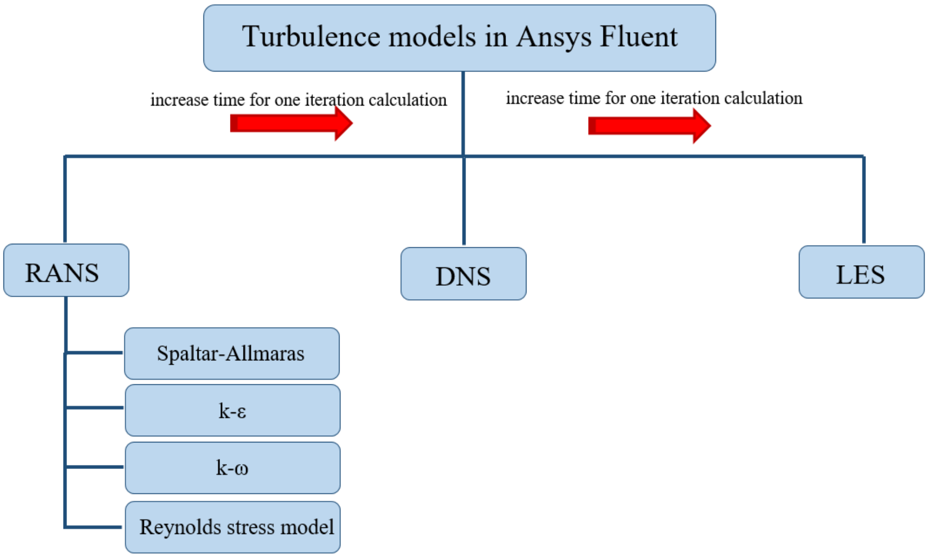

Fig. 2. Turbulence models in the Ansys Fluent software (RANS - Reynold Averaged Navier-Stokes; DNS - Direct Numerical Simulation; LES - Large Eddy Simulation)

For the numerical calculation, there was used the „*k-ε*" turbulence in standard variation model belonging to semi-empirical models, characterising by parameters determined based on experimental tests. This model describes components of Reynolds turbulent stress tensor according to the Boussinesq hypothesis.

Area of research

The basic calculation model was built by means of the real geometrical and ventilation parameters of the driven dog heading in one of the Polish hard coal mines. The basic geo-mining parameters of driven dog heading are as follows:

- Airflow rate: ~ 302 m^3/min;
- Gas emission: ~ 4,0 kg/min;
- The geometry of driven dog heading (height × length × width): 3,0 m × 60,0 m× 4,0 m;
- The length of air duct: 57,0 m;
- The diameter of auxiliary ventilation: 0,8 m.

As already mentioned in the introduction, the model also includes the fracture zone around the dog heading. Due to its permeability, methane migrates from this zone to the driven dog heading. The dog heading model also contains its technical equipment such as air-duct lines, a conveyor and a roadheader. The model of the studied dog heading with marked flow directions, the fracture zone, as well as measurement points and lines, are shown in Figure 3.

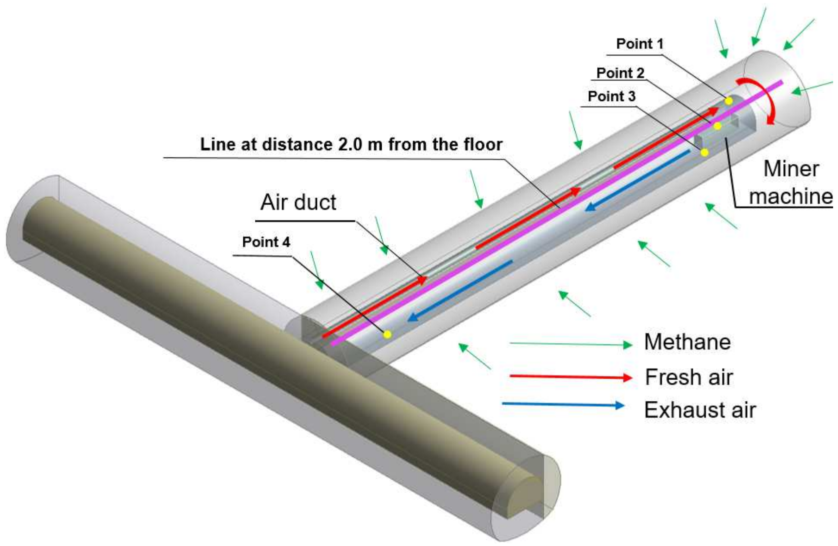

Fig. 3. The geometry of the computational domain of underground driven dog heading with equipment and measurement points and line

The studies were carried out for the real system (Fig. 4a) and three additional locations of air-duct lines in the studied dog heading. The distribution diagrams of the air-duct lines for the studied variants are shown in Figure 4.

The model, along with adopted simplifications, was subjected to numerical analysis. Calculations were made in the ANSYS Fluent 18.2 software. The pressure – velocity coupling and scheme Coupled algorithm, the second-order upwind discretization method and the algebraic multigrid method were used to solve the equations mass, momentum, energy and species transport.

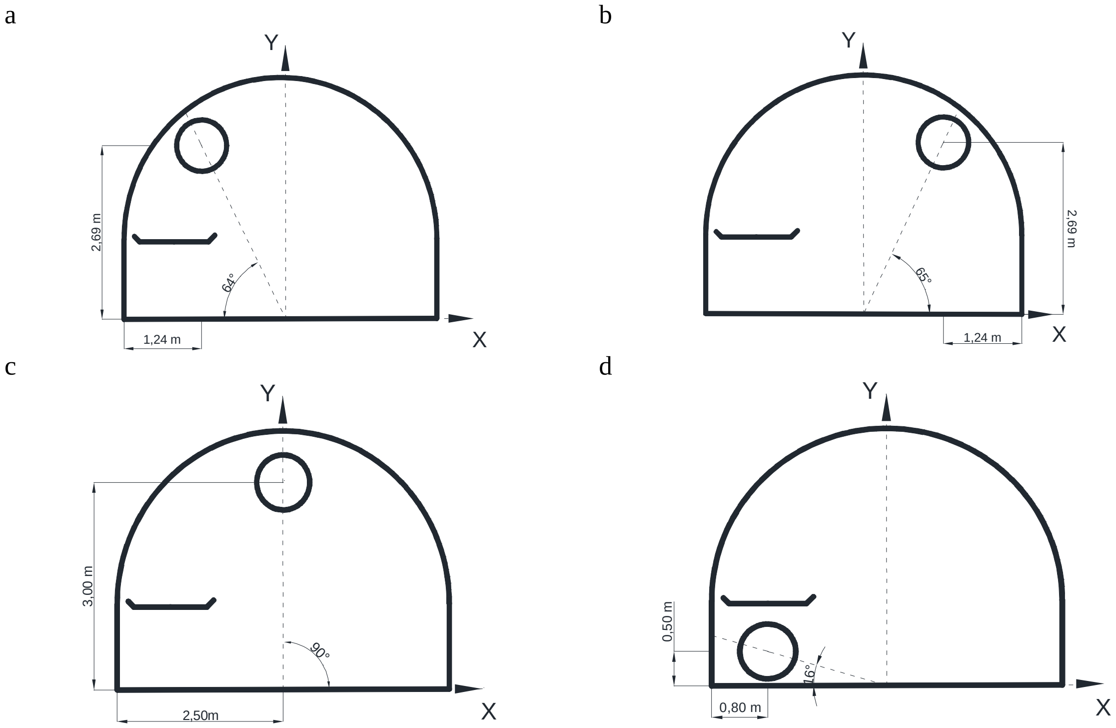

Fig. 4. Distribution diagrams of the air-duct lines for the studied variants (a - left side (constitutes real variants); b – right side; c – the central part of dog heading and d – under conveyor)

Results and Discussion

Based on the analyses, the number of parameters related to the flow of air and methane mixture in the studied dog heading were determined.

Airflow trajectories through the driven dog heading were determined in the first stage of studies for all analysed location variants of the air-duct lines. The way of airflow through this dog heading has a significant impact on the areas of local methane accumulations. The airflow trajectories through the driven dog heading for studied location variants of the air-duct lines are shown in Figure 5.

The analysis of the determined trajectories clearly shows that the largest flow disturbances were reported in the face zone of the driven dog heading (mining zone). An air stream flowing out of the air-duct lines hits the unmined coal being worked on. After bouncing off, it flows through the entire length of the underground dog heading. This creates a vortex movement and air recirculation in the face zone. The phenomenon of the impact of the airstream on the unmined coal leads to the creation of large curvatures of the current line.

The presented trajectories also reveal that taking into account the fracture zone around the driven dog heading leads to a situation where the small amounts of air forced into the face of the driven dog heading, regardless of the location of the air-duct lines, can migrate to the zone in question. This phenomenon disturbs the dog heading ventilation process, which may also be the reason for low-temperature coal oxidation in the fractured side wall (Szurgacz et al., 2019; Tutak and Brodny, 2019). This, in turn, can lead to the occurrence of endogenous fire, which is confirmed by the statistics of endogenous fires in the wall sides and ceilings of driven dog headings (Wyższy Urząd Górniczy, 2019).

On the other hand, the phenomenon of air migration deep into the rock mass through the fracture zone reduces the amount of methane released into the dog heading.

Distributions of methane concentration in cross-sections of the driven dog heading for individual variants are presented in Figure 6. These distributions were located every 10.0 m from the dog heading face. The distribution shown in Figure 6a corresponds to the real system.

a

b

c

d

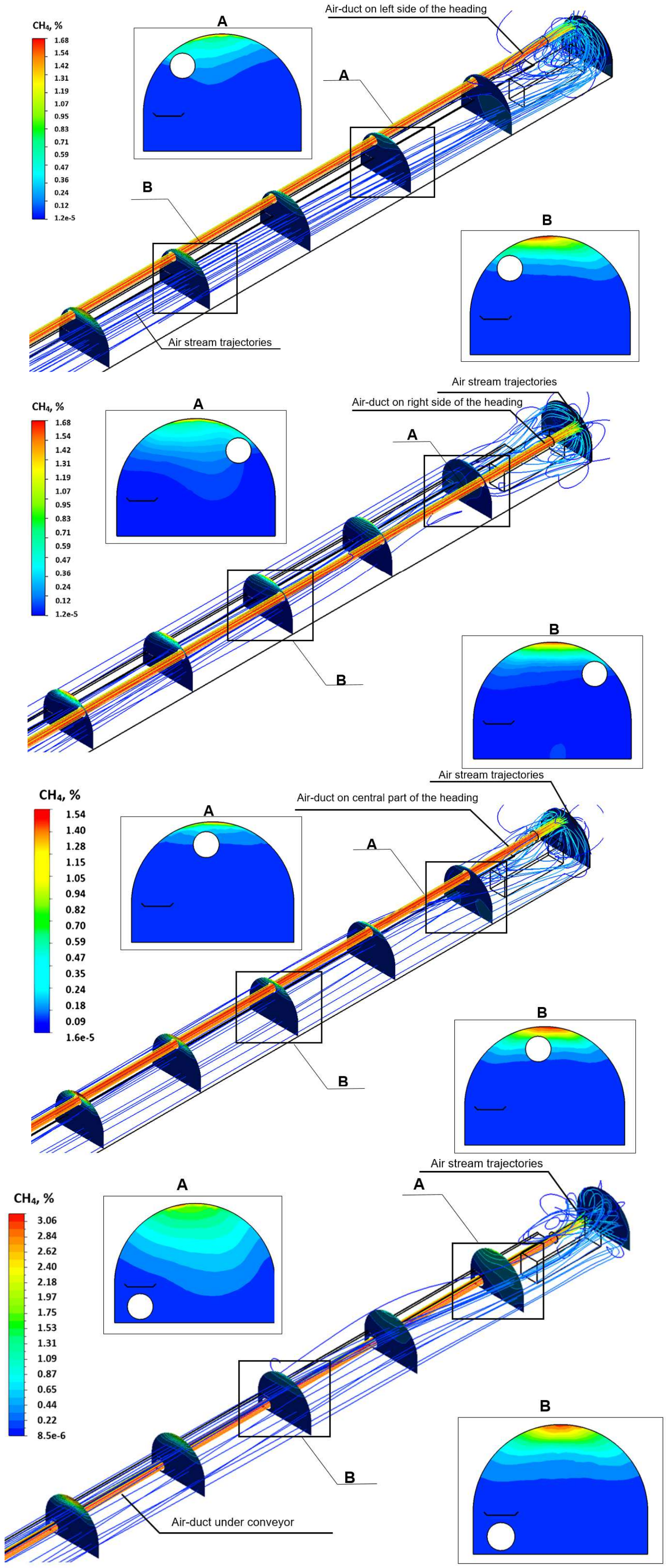

Fig. 5. Distribution of methane concentration in cross-sections of the driven dog heading for different location of air-duct (a - left side; b – right side; c – the central part of dog heading and d – under conveyor)

When analysing the obtained distributions, it can be stated that the location of the air-duct lines in the driven dog heading affects methane distribution and concentration in the studied dog heading. The conducted analyses showed that the most unfavourable situation occurs for the air-duct lines on the thill of the dog heading. For this variant, the local methane concentration levels may exceed 3% (Fig. 5d), while in other cases, these concentration levels do not exceed 1.66%.

The reason for this is the fact that methane, as a gas lighter than air, accumulates near the ceiling of the dog heading, and the air stream flowing out of the air-duct line located on the thill has less impact on the upper part of the dog heading, which creates a zone with higher methane concentration levels.

The most favourable location of the air-duct line in the dog heading is its central part, i.e. for case 3 (Fig. 5c).

The distribution of methane concentration levels in vertical sections of the driven dog heading was also found to be worth mentioning. The results obtained in the cross-sections for studied variants are shown in Figure 6. Due to the fact that during the calculations in the area of boundary conditions “outlet”, the reserved flow phenomenon occurred.

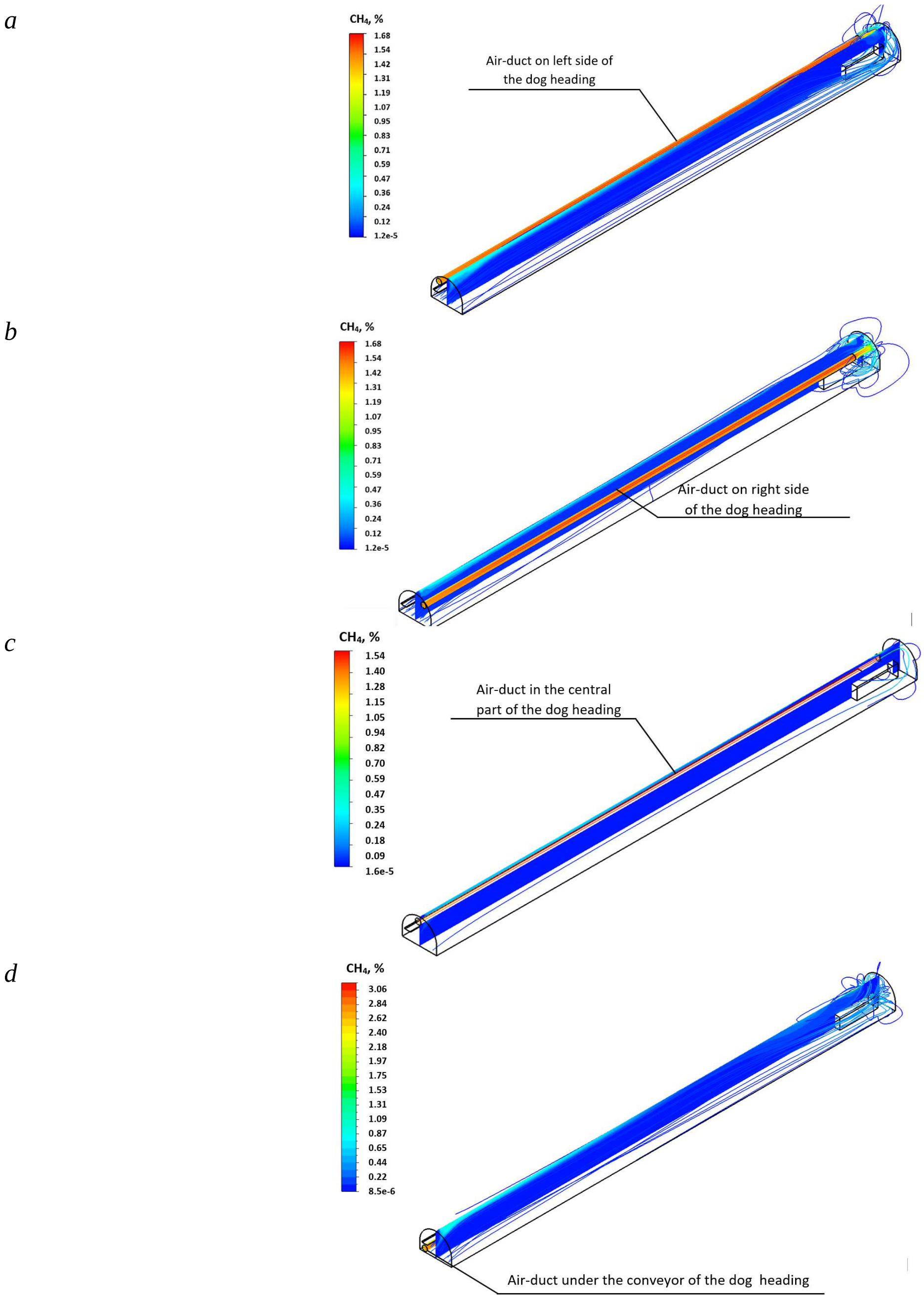

Fig. 6. Distribution of methane concentration in cross-sections of the driven dog heading for different location of air-duct (a - left side; b – right side; c – the central part of dog heading and d – under conveyor)

The results also enabled the determination of the methane concentration value at any point of the dog heading. In order to better illustrate the changes in the value of methane concentration in this dog heading, they were determined for the measurement line.

Figure 7 presents the values of methane concentration levels along the measurement line for studied location variants of the air-duct lines in the driven dog heading.

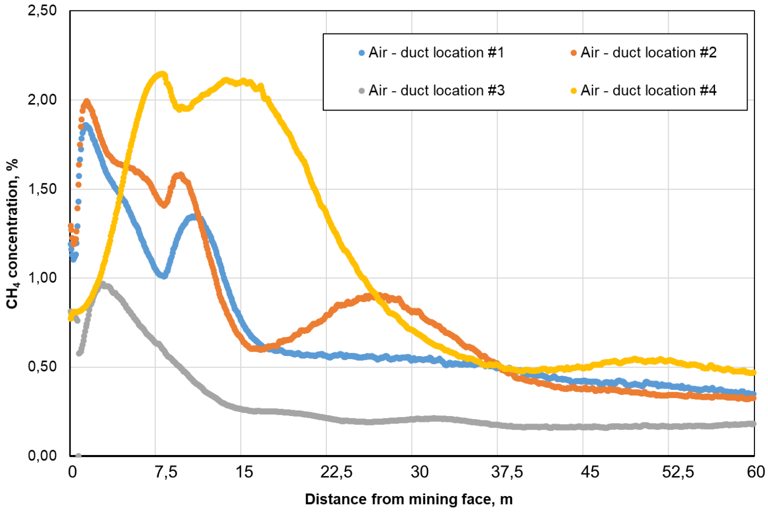

Fig. 7. The distribution of methane concentration along the measurement line in the heading for different location of air-duct (location #1-left side; location #2 – right side; location #3 – the central part of dog heading and location #4 – under conveyor)

Based on the analysis of the results, it can be concluded that the highest methane concentration levels were reported at an altitude of 2.0 m from the thill of the dog heading, along its entire length for all studied variants. These results confirmed that the location of the air-duct lines affects the distribution and, consequently, methane concentration levels in the dog heading.

The lowest methane concentration levels along the measurement lines were reported in the dog heading with air-duct lines located in the central part of the dog heading, under the ceiling (case 3). However, the highest methane concentration levels were observed in the dog heading with air-duct lines located on the thill, under the conveyor (case 4). This is clearly the most unfavourable location of the air-duct lines in the dog heading.

For the variant with air-duct lines located at the sidewall opposite the conveyor (case 2), at a level of around 20 meters, a local increase in methane concentration levels was noted. This phenomenon may be associated with the occurrence of intensive recirculation flow, which is confirmed by the airflow trajectories shown in Figure 5b. The recirculation phenomena can lead to the creation of a zone with weaker air exchange and local elevated methane concentration levels. Around 30 meters from the face, a decrease in the methane concentration values for this variant was shown. This increase applies especially to the measurement line located at a distance of 2.0 m from the thill of the dog heading.

The accuracy of the results was assessed by comparing them with the measurement values in real conditions (for variant 1). The measurement of methane concentration in Polish mines is a point (local) measurement, and it is carried out only in specified places (points). In this case, the location of control points in the numerical model coincided with the location of the automatic methane measurement sensors (Fig. 8).

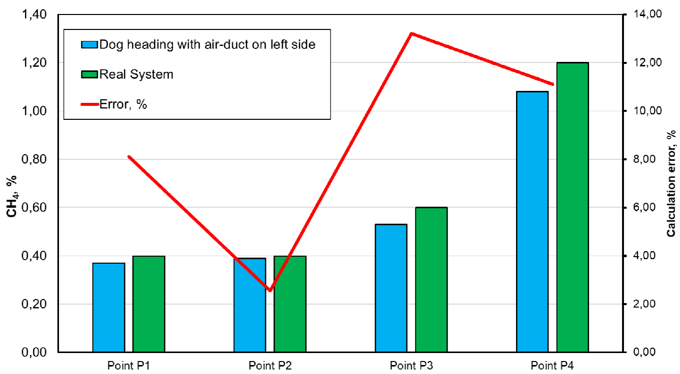

Fig. 8. The comparison of methane concentration values obtained from the measurements in real dog heading with air-duct on the left side and determined from the model studies for the variant with air-duct on left side

Conclusions

The methane hazard is one of the most common and dangerous threats reported in underground hard coal mines. Therefore, for the mining production process, the goal is to avoid a situation in which methane concentration levels in the mine atmosphere reach critical values that may result in either its ignition or explosion. This problem particularly applies to dog headings, which, due to the one-sided connection with the central ventilation system, are particularly exposed to the occurrence of hazardous methane concentration levels.

The methodology of model studies developed and presented in the paper, based on the results of measurements in real conditions, creates great possibilities for the analysis of ventilation conditions in mine headings. The publication focuses on the analysis of the impact of air-duct lines on the distribution and concentration of methane in driven dog headings. The results clearly indicate that the location of air-duct lines has an impact on the distribution of methane concentration in the studied dog heading. These results also enable the location of areas where hazardous concentrations of this gas may occur, which is a valuable source of information for ventilation services.

Both the studies and the results also point to potential areas where air-duct lines can be located and those where it is inadvisable. This is particularly important information when choosing a proper location for them (for example, if limited for technical reasons), or in the event where it is necessary to install an emergency air-duct. In such cases, the results clearly show locations where, for example, methane concentration values should be monitored.

The idea of taking into account the fracture zone around the studied dog heading is also a very essential and undoubtedly valuable achievement of this paper. Undoubtedly, the size of this zone and its permeability has an impact on the physical parameters of the air and gas stream in the dog heading. Its inclusion in the analysis enabled more accurate mapping of real conditions.

It should also be emphasised that the tests and the results broaden knowledge in the field of ventilation system studies. This is particularly crucial for underground mine workings, where ventilation hazards are still being reported, leading to immensely dangerous events.

Therefore, effective forecasting of methane concentration in mine workings is extremely important from the point of view of ensuring the safety of both miners and equipment. The results also prove that the use of model studies combined with the results of tests in real conditions can be successfully utilised for variant analyses of processes related to the ventilation of underground mine workings, as well as in analyses of emergency conditions. These activities should also support the forecasting of ventilation hazards in mine workings.

In addition, it needs to be highlighted that the developed methodology is universal and can be used to analyse other objects.

References

ANSYS. (2011). Ansys Theory Guide; ANSYS, Inc.: Canonsburg, PA 15317., USA.

Baranov, M., Bozek, P., Prajova, V., Ivanova, T., Novokshonov, D., and Korshunov, A. (2017). Constructing and calculating of multistage sucker rod string according to reduced stress. *Acta Montanistica Slovaca, Vol. 22, Issue: 2, pp. 107-115*.

Biały, W. (2013). New devices used in determining and assessing mechanical characteristics of coal. 13th SGEM GeoConference on Science and Technologies In Geology, Exploration and Mining, SGEM2013 Conference Proceedings, June 16-22, 2013, Vol. 1, BUŁGARIA ISBN 978-954-91818-7-6/ISSN 1314-2704. pp. 547-554.

Biały, W. (2014). Coal cutting force measurment systems - (CCFM). 14th SGEM GeoConference on Science and Technologies In Geology, Exploration and Mining, SGEM2014 Conference Proceedings, June 17-26, 2014, Vol. III, BUŁGARIA ISBN 978-619-7105-09-4/ISSN 1314-2704. pp. 91-98.

Biały, W. (2018) Application of quality management tools for evaluating the failure frequency of cutter-loader and plough mining systems. *Archives of Minning Sciences, Volume 62, issue 2, 2017. pp. 243-252*. ISSN 0860-7001. DOI 10.1515/amsc-2017-0018

Biały, W. and Fries, J. (2019) „Computer Systems Supporting the Management of Machines/Equipment in Hard Coal Mines. Case Study" *Management Systems in Production Engineering, Volume 27 issue 3/2019. pp. 138-143*. ISSN 2299□0461. DOI 10.1515/mspe-2019-0022

Brodny, J. (2010). Determining the working characteristic of a friction joint in a yielding support. *Archives of Mining Sciences, 55(4), pp. 733–746*.

Brodny, J. (2011). Tests of friction joints in mining yielding supports under dynamic load. *Archives of Mining Sciences, 56(2), pp. 303–318*.

Brodny, J. (2012). Analysis of operation of new construction of the frictional joint with the resistance wedge. *Archives of Mining Sciences, 57(1), pp. 209–227.*

Brodny, J. and Tutak, M. (2015). Numerical analysis of airflow and methane emitted from the mine face in a blind dog heading. *Management Systems in Production Engineering, 5(2), pp. 110-118*.
Brodny, J., Alszer, S., Krystek, J. and Tutak, M. (2017). Availability analysis of selected mining machinery. *Archives of Control Sciences, 27(2), pp. 197-209.*
Brodny, J., Tutak, M. and John, A. (2018). The impact of airway geometry on the distribution of methane concentrations at the outlet from a longwall. *Mechanika, 24(5), pp. 695-702*.
Brodny, J. and Tutak, M. (2019). Analysing the Utilisation Effectiveness of Mining Machines Using Independent Data Acquisition Systems: A Case Study. *Energies 12, 2505.*
Cernecky, J., Valentov, K., Pivarciova, E. and Bozek, P. (2015). Ionization Impact on the Air Cleaning Efficiency in the Interior. Measurement science review, Vol. 15, Issue 4, p. 156-166
Kalentev, E., Vaclav, S., Bozek, P., Tarasov, V. and Korshunov, A. (2017). Numerical analysis of the stress-strain state of a rope strand with linear contact under tension and torsion loading conditions. *Advances in science and technology-research journal, 11(2) 2, pp. 231-239.*
Krause, E. (2015). Short-term predictions of methane emissions during longwall mining. *Archives of Mining Sciences, 60(2), pp. 581–594*.
Kurnia, J.C., Sasmito, A.P. and Mujumdar, A.S. (2014a). CFD simulation of methane dispersion and innovative methane management in underground mining faces. *Applied Mathematical Modelling, 38(14), pp. 3467–3484.*
Kurnia, J.C., Sasmito, A.P. and Mujumdar; A.S. (2014b). Simulation of a novel intermittent ventilation system for underground mines. *Tunnelling and Underground Space Technology, 42, pp. 206–215.*
Kurnia, J.C., Xu, P. and Sasmito, A. (2016). A novel concept of enhanced gas recovery strategy from ventilation air methane in underground coal mines e A computational investigation. *Journal of Natural Gas Science and Engineering*, 35, pp. 661-672.
Ordinance of the Minister of Energy *On detailed requirements for conducting underground mining operations* of 23 November 2016 (Journal of Laws of 2016, No. 2017, item 1118, as amended).
Małkowski, P., Ostrowski, Ł. and Bachanek, P. (2017). Modelling the Small Throw Fault Effect on the Stability of a Mining Roadway and Its Verification by In Situ Investigation. *Energies, 10, 2082.*
Masny, W., Prusek, S., Mutke, G. (2017). Numerical Modeling of the Dynamic Load Changes Exerted on the Support in the Stress Concentration Zones. *Procedia Engineering, 191, pp. 894-899.*
Prusek, S. and Walantek, A. (2005). Wielkość strefy zniszczenia górotworu wokół wyrobiska korytarzowego w oparciu o kryteria Hoeka-Browna. *Prace Naukowe GIG. Seria Konferencje, 49, pp. 13–24*.
Prusek, S. (2008). Modification of parameters in the Hoek-Brown failure criterion for gate road deformation prediction by means of numerical modeling. *Glückauf*, 9, pp. 529-534.
McPherson, M.J. (1993). Subsurface Ventilation and Environmental Engineering. Chapman & Hall, New York.
Roghanchi, P., Kocsis, K. and Sunkpal, M. (2016). Sensitivity analysis of the effect of airflow velocity on the thermal comfort in underground mines. *Journal of Sustainable Mining, 15(4), pp. 175–180*.
Sasmito, A.P., Birgersson E., Hung C. and Mujumdar, A.S. (2013). Some approaches to improve ventilation system in underground coal mines environment – A computational fluid dynamic study. *Tunneling and Underground Space Technology, 34, pp.82–95.*
Szurgacz, D., Sobik, L. and Brodny, J. (2019). Integrated method of reducing the threat of endogenous fires in hard coal mines. *E3S Web of Conferences, 105, 01013.*
Tuliszka–Sznitko, E. (2011). Wybrane zagadnienia z mechaniki płynów wirujących. WPP, Poznań.
Tutak, M. and Brodny, J. (2018). Analysis of the impact of auxiliary ventilation equipment on the distribution and concentration of methane in the tailgate. *Energies 11*, 3076.
Tutak, M. and Brodny, J. (2019). The Impact of the Strength of Roof Rocks on the Extent of the Zone with a High Risk of Spontaneous Coal Combustion for Fully Powered Longwalls Ventilated with the Y-Type System—A Case Study. *Applied Sciences, 9, 531*.
Tutak, M. (2020). The Influence of the Permeability of the Fractures Zone Around the Heading on the Concentration and Distribution of Methane. *Sustainability, 12, 16*.
Veersteg, K.K. and Malalasekera, W. (2007). An Introduction to Computational Fluid Dynamics. The Finite Volumne Method; Pearson Education: London, UK.
Wyższy Urząd Górniczy. (2019) Available online http://www.wug.gov.pl/bhp/stan_bhp_w_gornictwie (accessed on 15 November 2019).
Xiu, Z., Nie, W., Yan, J., Chen, D., Cai, P., Liu, Q., Du, T. and Yang, B. (2019). Numerical simulation study on dust pollution characteristics and optimal dust control air flow rates during coal mine production. *Journal of Cleaner Production*, 119197.
Yang, H., Han, C., Zhang, N., Sun, C., Pan, D. and Dong, M. (2019). Stability Control of a Goaf-Side Roadway under the Mining Disturbance of an Adjacent Coal Working Face in an Underground Mine. *Sustainability, 11, 6398*.

Zhao, J., Qin, Y., Shen, J., Zhou, B., Li, C. and Li, G. (2019). Effects of Pore Structures of Different Maceral Compositions on Methane Adsorption and Diffusion in Anthracite. *Applied Sciences*, *9, 5130*.

Zhou, G., Zhang, Q., Bai, R., Fan, T., Wang, T. (2017). The diffusion behavior law of respirable dust at fully mechanized caving face in coal mine: CFD numerical simulation and engineering application. *Process Safety and Environmental Protection*, 106, pp. 117-128.