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Analysis of The Effects of the Position of the Air DuctSupplying Fresh Air to the Working Face of the Mined DogHeading on Methane Concentration Levels

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Abstract. Each year, more than one hundred kilometres of new dog headings are mined in underground hard coal mines. Such headings are ventilated by means of an air duct system. A stream of fresh air is supplied to the working face of the mined heading through an air duct with a view to ensuring proper chemical composition and temperature of the mining atmosphere. This is because this heading is being exploited and the ventilation must provide adequate working conditions for the crew. While dog headings are being mined in the body of coal, they are additionally filled with methane, which is released in this process. Due to the risk of its combustion and explosion, methane is a highly dangerous gas. It represents one of the greatest hazards in underground mining. Therefore, a particularly essential issue during the mining of dog headings is to reduce the potential for dangerous methane concentrations to occur. To prevent this from happening, it is necessary to select adequate parameters for the fresh air supplied through the air duct and the position of this air duct. It is the position of the air duct that appears to be a very significant element in the ventilation process of dog headings. Model-based tests were conducted to determine how the position of the air duct affects methane concentration levels. Their results have been presented in the paper. The tests were conducted using Computational Fluid Dynamics (CFD). The related calculations were performed in ANSYS Fluent, based on the finite volume method (FVM). The analyses performed made it possible to identify the concentrations levels of methane and the physical parameters of the flowing gas mixture at each spatial point of the area under examination, for the boundary conditions adopted. The purpose of the tests was to determine whether and to what extent the position of the air duct, which is used to supply fresh air to the mined dog heading, influences methane concentration in this heading. The tests were conducted for an actual mining region in which a dog heading was mined. The input parameters for the model (boundary conditions) were therefore adopted from the actual system. The model-based tests helped to determine the distributions for methane concentration depending on the position of the air duct. The analysis mainly encompassed the distance between the outlet of the air duct and the surface of the mined body of coal. The use of model-based tests which employed numerical methods made it possible to determine a series of significant physical and chemical parameters of the resulting mixture of gases. Their distributions and values in selected points for the variants under analysis have been presented in the paper. The results obtained unambiguously demonstrate that the position of the air duct has a significant impact on the distributions of methane concentration levels in the mined dog heading. In the Authors’ opinion, these results may constitute an essential source of information for service teams responsible for ensuring ventilation-related safety in mines. This is because they allow for predicting the distribution of methane concentration and other parameters of the gas mixture that occurs in dog headings during the mining process.
1. Introduction

Each year, more than one hundred kilometres of new dog headings are mined in underground hard coal mines [1, 2, 3, 4]. Driven dog headings are blind dog headings, i.e. they have only one connection with the air flow routes. Such headings are ventilated by means of an air duct system (Fig. 1).

A stream of fresh air is supplied to the working face of the mined heading through an air duct with a view to ensuring proper chemical composition and temperature of the mining atmosphere [5, 6]. While dog headings are being mined in the body of coal, they are additionally filled with methane, which is released in this process. Due to the risk of its combustion and explosion, methane is a highly dangerous gas [7, 8, 9, 10, 11, 12, 13]. In the years 2008-2018 alone, there were 34 dangerous methane-related incidents in the Polish hard coal mining, with 10 occurring in dog headings mined in coal seams [14].

It represents one of the greatest hazards in underground mining. Therefore, a particularly essential issue during the mining of dog headings is to reduce the potential for dangerous methane concentrations to occur. To prevent this from happening, it is necessary to select adequate parameters for the fresh air supplied through the air duct and the position of this air duct. It is the position of the air duct that appears to be a very significant element in the ventilation process of dog headings. Model-based tests were conducted to determine how the position of the air duct affects methane concentration levels. Their results have been presented in the paper.

The tests were conducted using Computational Fluid Dynamics (CFD). The related calculations were performed in ANSYS Fluent, based on the finite volume method (FVM). The analyses performed made it possible to identify the concentrations levels of methane and the physical parameters of the flowing gas mixture at each spatial point of the area under examination, for the boundary conditions adopted.

The purpose of the tests was to determine whether and to what extent the position of the air duct, which is used to supply fresh air to the mined dog heading, influences methane concentration in this heading. The tests were conducted for an actual mining region in which a dog heading was mined. The input parameters for the model (boundary conditions) were therefore adopted from the actual system.

The model-based tests helped to determine the distributions for methane concentration depending on the position of the air duct. The analysis mainly encompassed the distance between the outlet of the air duct and the surface of the mined body of coal. The use of model-based tests which employed numerical methods made it possible to determine a series of significant physical and chemical parameters of the resulting mixture of gases. Their distributions and values in selected points for the variants under analysis have been presented in the paper. The results obtained unambiguously demonstrate that the position of the air duct has a significant impact on the distributions of methane concentration levels in the mined dog heading.
2. Materials and Methods

The purpose of the model-based tests conducted was to determine the impact of auxiliary ventilation equipment installed in the tailgate on the distribution of methane concentration in the blind dog heading. The tests were conducted for a spatial model of the area under analysis, using Computational Fluid Dynamics (CFD). The Authors’ experiences and the results by other researchers indicate that this method is widely applied for analysing phenomena related with the flows of fluids and gases, the transfer of mass and heat or the processes of combustion [12].

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

The air flows at blind dog heading are simulated as fully developed turbulent flow by using an $k$-$\varepsilon$ realizable model.

2.1. Basic flow equations

The system of balance equations of mass, momentum and energy (equations of fluid handling) of one-component flow takes the following form [15]:

\[
\frac{\partial}{\partial t} (\rho) + \text{div} \left( \rho \, v \right) = 0
\]  

\[
\frac{\partial}{\partial t} (\rho \, v) + \text{div} \left( \rho \, v \, v \right) = \text{div} \left( -p \, I + \tau + \tau \right) + \rho \, s_b
\]  

\[
\frac{\partial}{\partial t} (\rho \, e) + \text{div} \left( \rho \, e \, v \right) = \text{div} \left[ -p \, I + \tau + \tau \right] v + q_s + q_t + \rho \, s_e
\]

The system of equations (1-3) in a vector form can be written as [15]:

\[
\frac{\partial}{\partial t} \begin{pmatrix} \rho \\ \rho \, v \\ \rho \, e \end{pmatrix} + \text{div} \begin{pmatrix} \rho \, v \\ \rho \, v + p \, I \\ \rho \, e + p \, I \, v \end{pmatrix} = \text{div} \begin{pmatrix} 0 \\ \epsilon \, m + \epsilon \, R \\ \epsilon \, m + \epsilon \, R \end{pmatrix} \begin{pmatrix} \rho \, s_p \\ \rho \, s_b \\ \rho \, s_e \end{pmatrix}
\]

The variables presented in the system of equations (2-5) are [15]:

\[
\begin{pmatrix} \rho, v, p, \tau, \epsilon, s_p, s_b, s_e, q_s, q_t \end{pmatrix}
\]

where: where: $\rho$ is the fluid density (kg/m$^3$), $v$ is the air velocity (m/s), $p$ is the static pressure (Pa), $\tau$ is viscous molecular stress tensor (Pa), $\epsilon$ is turbulent Reynolds stress tensor (Pa), $s_b$ is sources of forces (N/m$^2$), $e$ is the sum of kinetic and internal energy (J/kg), $q$ is molecular heat flux (J/(m$^2$-s)), $q$ is turbulent heat flux (J/(m$^2$-s)), $S$, is sources of heat (J/(m$^3$-s)).

The basis for a mathematical description of the transportation process of methane released into underground headings is the principle of mass conservation referred to this gas. The mathematical model of transportation, being a set of advection–diffusion equations, which for $i$- of this substance $i=1,\ldots,n$, assumes the following form [12]:

\[
\begin{align*}
\frac{\partial}{\partial t} \left( \rho \, v_i \right) + \text{div} \left( \rho \, v_i \, v_i \right) & = \text{div} \left( -p \, I + \tau_i + \tau_i \right) + \rho \, s_{bi} \\
\frac{\partial}{\partial t} \left( \rho \, e_i \right) + \text{div} \left( \rho \, e_i \, v_i \right) & = \text{div} \left[ -p \, I + \tau_i + \tau_i \right] v_i + q_{si} + q_{ti} + \rho \, s_{ei}
\end{align*}
\]
\[
\frac{\partial}{\partial t} (\rho_i Y_i) + \nabla \cdot (\rho_i \nu_i Y_i) = -\nabla \cdot J_i + R_i + S_i \tag{6}
\]

where: \( R_i \) is 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.

2.2. Constitutive equations

A ternary species mixture comprising oxygen, water vapour and methane exists in the ventilation air in the mining headings.

Mixture molar mass is given by [16, 17]:

\[
M = \left[ \frac{\omega_{O_2}}{MO_2} + \frac{\omega_{CH_4}}{MCH_4} + \frac{\omega_{N_2}}{MN_2} + \frac{\omega_{H_2O}}{MH_2O} \right]^{-1} \tag{7}
\]

where: \( M \) is the molar mass of species \( i \).

The air-methane mixture viscosity is calculated as [16, 17]:

\[
\mu = \sum_i \sum_j x_i \phi_{i,j} \frac{x_j \mu_j}{M_i} \tag{8}
\]

where: \( x_{i,j} \) are the mole fraction of species \( i \) and \( j \) and [16, 17]:

\[
\phi_{i,j} = \frac{1}{\sqrt{8}} \left( \frac{M_i}{M_j} \right)^{\frac{1}{2}} \left[ 1 + \left( \frac{\mu_j}{\mu_i} \right)^{\frac{1}{2}} \left( \frac{M_i}{M_j} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} \tag{9}
\]

The mole fractions are related to the mass fractions by [16, 17]:

\[
x_i \equiv \frac{\omega_i M}{M_i} \tag{10}
\]

For practical purpose, methane concentration in terms is present of percentage of methane concentration, defined as \( CH_4 = \omega_{CH_4} x 100\% \).

3. Problem statement and boundary conditions

In order to perform an analysis, geometrical model of dog heading with air-duct, conveyor belt and roadheader was developed.

The length of the heading was 50 m, whereas its width in the floor amounted to 4.0 m. The model included an in-built air duct supplying air to the mined heading. The diameter of the ventilation pipe (air duct) is equal to 0.8 m.

The tests were conducted for three different distances between the outlet from the air duct and the mined body of coal. The distance between the outlet and the mined surface of the body of coal is marked with the “L” symbol in Figure 2.

The basic geometric, ventilation, and calculation parameters of the model are presented in Figure 2.
Figure 2. 3D model of the dog heading and the duct.

The main parameters are presented in Table 1.

| Name                              | Parameter setting |
|-----------------------------------|-------------------|
| Air density, kg/m³                | 1.225             |
| Methane density, kg/m³            | 0.656             |
| Total Air Flow, m³/min            | 301.44            |
| Total Methane Flow Rate, kg/s     | 0.01              |
| Diameter of air duct, m           | 0.8               |
| The location of the outlet from the air duct in relation to the dog heading face, m | 2.0, 4.0, 6.0 |

4. Results and discussions
Based on performed calculations the characteristics of changes of methane in air and distributions of methane concentration in driven dog heading were determined.
In Figure 3 there are presented changes of average methane percentage concentration in the air mixture as function of distance from mine face. In Figure 4 there are presented changes of maximum methane percentage concentration in the air mixture as function of distance from mine face.
Figure 3. Average methane concentration along the dog heading with sources at constant methane volume flow rate.

Figure 4. Maximum methane concentration along the dog heading with sources at constant methane volume flow rate.

In Figure 5 there is presented distribution of methane concentration in the mixture with air in the mined heading at plane 1, 5, 10, 15, 20, 25 m from the mining face for case 1.
Figure 5. Methane concentration (%) at plane 1, 5, 10, 15, 20, 25 m from the mining face for the dog heading for case 1.

In Figure 6 there is presented distribution of methane concentration in the mixture with air in the mined heading at plane 1, 5, 10, 15, 20, 25 m from the mining face for case 2.

Figure 6. Methane concentration (%) at plane 1, 5, 10, 15, 20, 25 m from the mining face for the dog heading for case 2.
In Figure 7 there is presented distribution of methane concentration in the mixture with air in the mined heading at plane 1, 5, 10, 15, 20, 25 m from the mining face for case 3.

Based on the calculations performed and the distributions of methane concentrations determined for the mine heading in question, it can be concluded that the distance between the outlet from the air duct and the surface of the mined body of coal affects the concentration levels of methane in this heading. The smaller the above-mentioned distance, the more diluted the methane present in this heading.

5. Conclusions
The article presents the results of numerical tests investigating the impact of the distance between the outlet from the air duct and the surface of the mined body of coal on the concentration levels of methane in this heading.

The results obtained unambiguously demonstrate that the position of the air duct has a significant impact on the distributions of methane concentration levels in the mined dog heading. The tests revealed that the smaller the distance between the outlet of the air duct and the surface of the mined body of coal, the more diluted the methane present in this heading.

In the Authors’ opinion, these results may constitute an essential source of information for service teams responsible for ensuring ventilation-related safety in mines. This is because they allow for predicting the distribution of methane concentration and other parameters of the gas mixture that occurs in dog headings during the mining process.

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