Analysis of the Consequences of Methane Combustion in a Mined Dog Heading

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Abstract. One of the most common and, at the same time, the most serious threats in underground hard coal mining, which often requires long rescue operations, is the methane hazard [1, 2, 3, 4, 5]. It is related to the potential ignition and/or explosion of methane in mixture with air. The hazard grows along with the increasing depth of mining works and the concentration of production in mine headings [6, 7, 8, 9, 10, 11, 12, 13]. Methane, as an organic gas, is released to the mining atmosphere in the exposed body of coal.

1. Introduction

One of the most common and, at the same time, the most serious threats in underground hard coal mining, which often requires long rescue operations, is the methane hazard [1, 2, 3, 4, 5]. It is related to the potential ignition and/or explosion of methane in mixture with air. The hazard grows along with the increasing depth of mining works and the concentration of production in mine headings [6, 7, 8, 9, 10, 11, 12, 13].

Methane, as an organic gas, is released to the mining atmosphere in the exposed body of coal.
Accumulation of explosive concentrations of methane in a mine heading, as well as adequate oxygen concentration levels and the presence of a trigger (e.g. in the form of a spark) may lead to methane explosion or combustion. Methane ignition in a mine heading may cause an underground fire.

An underground fire should be understood to include the occurrence of open fire, substances which are glowing or burning with open flames in an underground heading, as well as the detection of smoke or carbon oxide in the regional current of the mining air in the amount exceeding 25 dm³/minute [14].

Methane ignition and combustion leads to a series of chemical reactions, which cause the emission of harmful and poisonous gases of high temperature into the mining atmosphere (the temperature of methane combustion in mixture with air is approx. 1,875°C, with methane content of approx. 10%).

Countering the methane hazard primarily involves elimination of the potential for dangerous methane concentration levels and application of suitable protective measures to prevent methane ignition. However, despite the preventive measures in use, there were 34 incidents related to the methane hazard in Polish hard coal mines in the years 2008–2018, including 10 cases of methane ignition in the mined dog headings [15].

Therefore, it is necessary to carry out research in order to predict the consequences caused by methane combustion in mine headings.

Taking into consideration the remarks above, it was assumed that the numerical analysis of methane combustion in the mined dog heading and of the impact of this combustion on the parameters of the air stream flowing through this heading would be conducted using the CFD method.

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 objective of the analysis was to determine the effects of methane combustion on the composition of the mining atmosphere and the physical parameters of the gas mixture generated in this process. The paper presents the distributions for the physical parameters of the resulting gas mixture and the concentration of fire gases.

2. Governing equations

The tests were conducted for a model of the area under analysis, using 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 dust, 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 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.

2.1. Basic flow equations

The continuity equation for gas can be written as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho v_j) = 0$$  \hspace{1cm} (1)

Based on the law of mass conservation, the following expression can be acquired [16]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0$$  \hspace{1cm} (2)

The momentum equation can be written as:
\[
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]
\]

(3)

The energy equation can be written as [17]:

\[
\frac{\partial}{\partial x_j}(\rho c_i T) = -\frac{\partial}{\partial x_i} \left[ \left( \frac{\mu}{\rho} + \frac{\mu_t}{\sigma_j} \right) \frac{\partial T}{\partial x_i} \right] + \frac{q}{c_p}
\]

(4)

The kinetic energy equation of turbulent fluctuation (also known as \(k\)-equation) can be written as:

\[
\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]

(5)

The energy dissipation rate equation of the kinetic energy of turbulent fluctuation (also known as \(\varepsilon\)-equation) can be written as:

\[
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \rho \varepsilon} + C_1 \frac{\varepsilon}{k} C_3 G_b + S_\varepsilon
\]

(6)

2.2. Partially premixed combustion

Partially premixed combustion occurs if the fuel and oxidiser were mixed unevenly.

Turbulent flame combustion model for premixed flame and a PDF for turbulence chemistry coupling who calculates a progress variable \(c\) considering the 13 chemical species in chemical equilibrium [18].

The flame front propagation is modelled by solving a transport equation for the scalar quantity \(c\), the (Favre averaged) reaction progress variable [19]:

\[
\frac{\partial}{\partial t}(\rho c) + \nabla \cdot (\rho \mathbf{v} c) = \nabla \left( \frac{\mu_c}{s_c} \nabla c \right) + \rho S_c
\]

(7)

The progress variable is defined as [19]:

\[
c = \frac{\sum_{i=1}^{n} Y_{i, ad}}{\sum_{i=1}^{n} Y_{i, ad}}
\]

(8)

where: \(n\) is number of products, \(Y_i\) is mass fraction of species \(i\), \(Y_{i, ad}\) is mass fraction of species \(i\) after complete adiabatic combustion. Based on this definition, \(c=0\) where the mixture is unburnt and \(c=1\) where the mixture is burnt. The value of \(c\) is defined as a boundary condition at all flow inlets. It is usually specified as either 0 (unburnt) or 1 (burnt).

3. Problem statement and boundary conditions

In order to perform an analysis, geometrical model of dog heading with air-duct and roadheader was developed (Fig. 1).

The length of the heading was 45 m, whereas its height amounted to 3.7 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 outlet of air from the air duct was located at a distance of 4 meters from the front side of the mined heading face.

While modelling a combustion of methane, it was assumed to ignite at a distance of 0.5 m from the front of the mined heading face, at a height of 2.8 m (the ignition point is indicated in Figure 2). This ignition is caused by the sparks generated by the shearer system.
During the tests, records were being taken of the concentration levels of fire gases in the air stream as well as the temperature changes for these gases in the measurements points whose location is marked in Figure 2.

The calculations were performed for a transient state, for the time of 10 minutes (600 seconds). Another assumption was the variable emissions of methane from the front of the mined heading face. It was assumed that ignition occurs after 50 seconds of analysis and is initiated by a spark. The time course of methane mass stream emissions from the heading face is presented in Figure 3. It corresponds to the methane concentration changes actually registered in this heading while it was being mined.

![Figure 1. Model of the dog heading and the duct and the roadheader.](image1)

![Figure 2. Geometric model with measurement points (A and B) and point of methane ignition.](image2)

![Figure 3. The time course of methane mass stream emissions from the heading face.](image3)

4. Results and discussions

Based on the calculations performed, the changes in the concentration of gases from the air stream flowing through the heading under analysis were characterized as a function of time.

Figure 4 shows the time-dependent changes in the concentration levels of oxygen, methane, carbon monoxide and carbon dioxide as well as in the temperature in the measurement points A as a function of time.

Figure 5 shows the time-dependent changes in the concentration levels of oxygen, methane, carbon monoxide and carbon dioxide as well as in the temperature in the measurement points B as a function of time.
Figure 4. Time-dependent changes in the concentration levels of oxygen, methane, carbon monoxide and carbon dioxide as well as in the temperature in the first measurement point (A) as a function of analysis time.

Figure 5. Time-dependent changes in the concentration levels of oxygen, methane, carbon monoxide and carbon dioxide as well as in the temperature in the first measurement point (B) as a function of analysis time.

Figures 6 demonstrate the moment of the spark ignition appeared in the heading (t=50 s).

Figures 7 demonstrate the distributions of the mass fraction of oxygen and methane, in the heading, 20 seconds after start of methane combustion (t=70 s).
Figure 6. Distribution of progress variable in premixed combustion for the calculation time of $t=50$ seconds

Figure 7. Distribution of the mass fraction of oxygen (a), methane (b), carbon monoxide (c) and carbon dioxide (d) and temperature (d) in the heading for the calculation time of $t=70$ seconds
Figures 8 demonstrate the distributions of the mass fraction of carbon monoxide and carbon dioxide and temperature, in the heading, 20 seconds after start of methane combustion (t=70 s).

**Figure 8.** Distribution of the mass fraction carbon monoxide (a) and carbon dioxide (b) in the heading for the calculation time of t=70 seconds

Figures 9 demonstrate the distributions of temperature, in the heading, 20 seconds after start of methane combustion (t=70 s).
Figure 9. Distribution of temperature in the heading for the calculation time of $t=70$ seconds

5. Conclusions
The paper presents the distributions for the physical parameters of the resulting gas mixture and the concentration of fire gases. Moreover, it demonstrates the distributions for temperature and oxygen concentration levels in the heading under analysis. The objective of the analysis was to determine the effects of methane combustion on the composition of the mining atmosphere and the physical parameters of the gas mixture generated in this process.

Methane ignition and the ensuing fire in the confined space of a mine heading are very dangerous phenomena. They result in high temperatures and generate a series of products that are harmful to the environment and the crew. The analyses at hand unambiguously show the course of this phenomenon and the spread of the combustion products. It is obvious that the development of fires depends on the amount of the available fuel and oxygen. A constant inflow of air with a simultaneous, constant inflow of methane (which is often the case in dog headings) sustains the combustion process.

The model developed, the research conducted and the results obtained clearly indicate that model based tests can be successfully used for analysing fire events. It is extremely important for the mining sector as it allows forecasting the spread of fires and their consequences.

The analysis was conducted for an actual dog heading where no fire had occurred. The results obtained demonstrate what the consequences of such a fire would be and how it would be spreading.

In the Authors’ opinion, the method developed should be broadly applied to the forecasting of critical phenomena and to the training of crews on how to combat such phenomena once they occur.

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