Analysis of Influence of Goaf Sealing from Tailgate On the Methane Concentration at the Outlet from the Longwall

Magdalena Tutak¹, Jaroslaw Brodny²

¹ Silesian University of Technology, 44-100 Gliwice, Akademicka 2 Street, Poland  
² Silesian University of Technology, 41-800 Zabrze, Roosevelta 26-28 Street, Poland  
magdalena.tutak@polsl.pl

Abstract. One of the most common and most dangerous gas hazards in underground coal mine is methane hazard. Formation of dangerous, explosive concentrations of methane occurs the most often in the region of crossing of longwall with the ventilation gallery. Particularly it applies to longwalls ventilated in „U from bounds” system. Outflow of gases from the goaf to the tailgate takes place through the boundary surfaces of this sidewalk with goaf. Main cause of this process is a phenomenon of air filtration through the goaf with caving. This filtration is a result of migration of the part of ventilation air stream supplied to the longwall. This air is released into the goaf on the entire longwall length; however, its greater amount gets to the goaf with caving space at the crossing of maingate with exploitation longwall. Albeit, the biggest outflow of air mixture and gases from the goaf occurs in top gate in upper corner of the longwall. This is a result of pressure difference in this region. This phenomenon causes that to the space of heading besides the air also other gases present in the goaf, mainly methane, are released. Methane is an explosive gas. Most often boundaries of explosive mixtures of methane, air and inert gases are described by the so-called Coward triangle explosion. Within the limits of the occurrence of the concentration of explosive methane explosion initials may be endogenous fire, blasting or sparks arising from friction of moving lumps of rock. Therefore, in order to decrease its concertation in this region, by limiting its outflow from the goaf with caving different actions are taken. One of such action is sealing of goaf from top gate side. Analysis of impact of sealing of these goaf on the methane concentration at outlet from the longwall is main aim of studies researches. Model of tested region, together with boundary conditions (including parameters of flowing air and the methane content) was developed on the base of real data from one of the exploitation longwalls. In the studies it was assumed that measurement of sealing of goaf (their isolation) will be permeability coefficient of sealing layer. Based on this impact of this coefficient value on methane concentration at outlet from the longwall was determined. As a result of performed analysis also other physical parameters of air stream flowing through the tested region were determined, also dependent on the degree of sealing of goaf. Simulation tests were carried out with use of finite volume method. Obtained results clearly indicate, that by a proper selection of degree of sealing of goaf with caving, one can have significant influence on the air stream parameters in the region of upper corner of longwall.

1. Introduction
Underground exploitation of hard coal is very dangerous due to many natural hazards [1]. One of the most common and most dangerous natural hazards is methane hazard, which is connected to possibility of inflammation and/or explosion of methane mixed with air [2, 3, 4, 5, 6]. In the years
2005–2016 in Polish coal mines 36 hazardous events associated with methane hazard took place (inflammation and explosions of methane), in which 58 people died and 107 were injured. Formation of dangerous, explosive concentrations of methane occurs the most often in the region of crossing of longwall with the ventilation gallery. Particularly it applies to longwalls ventilated in „U from bounds” system. Nowadays, this system is applied in over 75% of all active mining longwalls in Polish hard coal mines. Accumulation of methane in this area is a result of its outflow from the goaf. Phenomenon of methane accumulation (A zone) can cause formation of disadvantageous events in a form of explosion and/or inflammation of methane.

Outflow of gases from the goaf to the tailgate takes place through the boundary surfaces of this sidewalk with goaf. Main cause of this process is a phenomenon of air filtration through the goaf with caving. This filtration is a result of migration of the part of ventilation air stream supplied to the longwall. This air is released into the goaf on the entire longwall length; however, its greater amount gets to the goaf with caving space at the crossing of maingate with exploitation longwall. However, the biggest outflow of air mixture and gases from the goaf occurs in top gate in upper corner of the longwall (zone A). This is a result of pressure difference in this region. This phenomenon causes that to the space of heading besides the air also other gases present in the goaf, mainly methane, are released.

There is the scheme of longwall ventilated (Figure 1), presented in the U type together with marked zone of particular hazard of occurrence of high methane concentration.

In order to prevent undesirable impact of gases, including methane, outflowing from goafs to the space of upper corner of the longwall (crossing of longwall with the bottom gate) isolation-sealing works in this region are performed.

These works include partial isolation of goafs from the top gate using different type of chemical, mineral media and materials with different sealing properties. Quality and precision of execution of this isolation has a significant influence on the methane concentration at the outlet from longwall. Studies of impact of sealing of goafs on the methane concentration at outlet from the longwall in the real conditions are very difficult. It results from the fact of conducting mining in this region and due to the safety. For this reason it is necessary to use other research methods. Such possibilities create model studies based on the numerical simulations.

These simulations are a widely applied research tool, which more common is used in many areas of science including variant analyses of processes associated with the outflow of gases in mining headings and in the analyses of faults.

In recently years, more and more widely for the analysis of ventilation problems related to the control of mining atmosphere composition in the mining headings numerical methods are used.

In the paper the results of numerical analysis aimed to determine the influence of sealing of goafs on the methane concentration at the outlet from the longwall are presented. Analyses were performed for 5 types of sealing materials (with different values of permeability coefficient of sealed layer). Additionally, influence of sealing of goafs also from the bottom gate side on the methane concentration value at outlet from the longwall (in upper corner) was also determined. For calculations ANSYS Fluent software based on finite volume method was used, which enable very precisely to
determine the physical and chemical air and methane mixture parameters at any point of tested mining heading. The analysis was performed for a real system of longwall with known dimensions and parameters of flowing air stream.

In Authors’ opinion, the obtained results can constitute a significant source of information for service responsible of operation safety in the investigated region. It applies specially to design and construction of appropriate sealing depending on the magnitude of methane hazard at the outlet from longwall.

2. Characteristics of media used for sealing of mining headings
Outflow of gases, mainly methane, from the goaf with caving causes a significant safety risk in the region of longwall for the working crew. One of way for decrease of this phenomenon is to seal the goaf with caving from side of the longwall gates. This sealing is carried out behind longwall frontage from the side of rested longwall gates near the goafs. This sealing is made from different type of materials, chemical and mineral agents.

The most often using materials to carry out these sealing are:
- floor cloth (textile) – strong and thick cloth, produced by weave technique with polypropylene strings, the most often used for battering of dams for hydraulic filling, passed water, stopped floor material;
- mining ventilation film – slow-burning, intended for sealing of ventilation dams, headings, goafs and all baffles and screens in underground headings of mining enterprises;
- polyurethane – plastic material used in the mining for sealing (polyurethane foams) and strengthen the mining heading (polyurethane glues);
- mineral wool – isolation material of mineral origin, used in mining for isolation of goafs by making of isolating floor belts;
- cement foam – material using in mining for building dams, sealing of floor plug, filling caverns or sealing active headings;
- adhesive preparation – chemical agent used for filling of gaps;
- anhydrite binder – used for building dams and isolated corks, making protective and isolating belts along the sidewalks, gunning mining headings and gaps behind frame, and firefighting prevention.

For agents which are used for sealing of mining headings, are subjected to different types of requirements, of which the most important are non-flammability, non-toxicity, antistaticity, elasticity, strength, ease of use and low cost. However, the value of permeability coefficient of isolation layer made of these agents (materials) is the most important.

In Table 1 values of permeability coefficients of selected isolation-sealing agents used for sealing mining headings are presented.

| Isolation-sealing agents | Permeability coefficients, m² |
|--------------------------|------------------------------|
| Floor cloth (textile)    | 9.41x10⁻⁶                   |
| Mining ventilation film  | 2.17x10⁻⁶                   |
| Polyurethane (test 3868) | 0.76x10⁻⁶                   |
| Mineral wool             | 0.045x10⁻⁶                  |
| Anhydrite binder         | 0.015x10⁻⁶                  |
| Cork of dry sand on floor cloth | 0.17x10⁻⁶         |
| Torkret handmade on floor cloth | 2.1x10⁻⁶               |
3. Mathematical model of gas flow

In order to determine particular hazardous zone of endogenous fires in goaf with caving, mathematical model of air stream flowing through porous medium based on below discussed dependences was developed.

A turbulent flow of viscous incompressible fluid (in this case a gas), was described by the Navier-Stokes system of equations, which together with continuity equation makes a complete system of relationships, allowing to determine pressure and field of flow velocity [8]:

- The continuity equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  

where: \( u, v, w \) are directions velocity (m/s), \( \rho \) is density (kg/m\(^3\)), and \( t \) is time (s).

- The momentum equation:

\[
\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot \tau + \rho g + F
\]

where: \( p \) is static pressure (Pa), \( \tau \) is the stress tensor (Pa), \( g \) is the gravitational body force (m/s\(^2\)) and \( F \) is the external body force (N).

The basis of the mathematical description of the transport process of the methane emission to the 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 \( i \)-th substance it takes the following form:

- The species transport equation

\[
\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho v Y_i) = -\nabla \cdot J_i + R_i + S_i
\]

where: \( v \) is velocity (m/s), \( Y_i \) is the local mass fraction of each species, \( J_i \) is the diffusion flux of species \( i \) (kg/(m\(^2\)s)), \( R_i \) 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.

- The mass diffusion in turbulent flows:

\[
J_i = -(\rho D_{i,m} + \frac{\mu_i}{S_{ci}^t}) \nabla Y_i
\]

where: \( D_{i,m} \) is the mass diffusion coefficient for species \( i \) in the mixture (m\(^2\)/s), \( \mu \) is the viscosity (Pa·s) and \( S_{ci} \) is the turbulent Schmidt number, 0.7.

Airflow through the goaf with caving is a flow through the porous medium. Therefore, to the equation of conservation of momentum, an additional source member \( S_i \) describing this flow was introduced:

\[
S_i = -\left( \frac{\mu_i}{k} + C_2 \frac{l}{2} \rho_s |v| v \right)
\]

where: \( S_i \) is the pressure loss items defined by Darcy’s law and \( C_2 \) is the inertial resistance factor.

Loss of momentum, described by the above equation, generates pressure gradient in the porous control volumes, which is proportional to its velocity and to the square of velocity in each volume of a liquid.
Flow of air stream through the exploitation longwall and segment of goaf with caving located just behind the sections of mechanical support, in which there was no full caving (determined by so-called caving step) does not correspond to laminar flow.

Flow of gas streams through the excavations has turbulent character, that is, in which irregular movement of air particles occurs, and its flow parameters undergoes to unpredictable random changes in space and time.

In the presented flow analysis, the „k-ε standard” turbulence model was applied. This model describes components of the Reynolds turbulent stress tensors according to the Boussinesq hypothesis. In the formula for the components of stress tensor there occur k and ε quantities. These quantities require additional two transport equations for single phase flows in a form:

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

\[
\rho \frac{\partial \varepsilon}{\partial t} + \rho \frac{\partial}{\partial x_j} \left( \rho u_j \varepsilon \right) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{2\varepsilon} \frac{\varepsilon}{k} \left( G_k + C_3 \varepsilon \right) - C_{1\varepsilon} \frac{\varepsilon^2}{k} + S_\varepsilon
\]

where: \( C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon} \) are constants, \( \sigma_k, \sigma_\varepsilon \) turbulent Prandtl numbers for \( k \) and \( \varepsilon \), \( G_k \) the generation of turbulence kinetic energy due to buoyancy, \( G_\varepsilon \) the generation of turbulence kinetic energy due to the mean velocity gradients, \( Y_M \) contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, \( S_k,S_\varepsilon \) user-defined source terms.

Therefore, presented model, takes into account both the flow of air stream, and the transport of gases.

4. The numerical research

Flow of air mixture and methane in the region of the crossing of longwall with ventilating roadway was subjected to analysis.

The aim of studies was to determine the influence of type of sealing of gafs on the methane concentration at the outlet of longwall. Tests were performed for 5 types of sealing materials and for 3 different systems (configurations) of sealing:
- without the sealing (Figure 2),
- sealing of goafs from the side of tailgate (Figure 3),
- sealing of goafs from the side of maingate and tailgate (Figure 4).

Figure 2. Geometrical models of tested area without the sealing
Model of tested region, together with boundary conditions (including parameters of flowing air and the methane content) was developed on the base of real data from one of the exploitation longwalls. In the studies it was assumed that measurement of sealing of goaf (their isolation) will be permeability coefficient of sealing layer.

Following types of goafs sealing materials were submitted to tests on the methane concentration at the outlet from longwall: floor cloth, ventilation cloth, polyurethane test 3867, anhydrite belt and mineral wool.

Modelling tests enabled to determine impact of sealing type on the methane concentration in the upper corner of longwall.

5. The tests result and discussions

As a result of performed simulations the methane concentration distributions in a region of longwall crossing with ventilation gate were determined. These distributions are determined depending on the type of seal and sealing system adopted (without the sealing, sealing of goafs from the side of tailgate and sealing of goafs from the side of maingate and tailgate).

In Figure 5 impact of permeability coefficient value of medium sealing the goaf with caving on methane concentration in upper corner of longwall is presented.

Obtained results clearly indicate the differences between methane concentration distributions at outlet from longwall depending on the type of sealing material and tested system.
Figure 5. a-f) Impact of permeability coefficient value of medium sealing the goaf with caving on methane concentration in upper corner of longwall

Application of sealing goafs, both from the bottom gate and from the top gate, influences on the methane concentration decrease at the outlet from longwall. Such a way of sealing of goaf with caving causes that permeation of air stream from the goafs is smaller.

This subsequently influences on the smaller difference between the aerodynamic potentials between the longwall and goaf with caving, which difference significantly limits the outlet of gases from goafs to the upper area of corner of longwall.
Based on performed calculations one can conclude that mineral wool is a material with the lowest permeability, and floor cloth is material with the highest permeability. Application of mineral wool as sealing material causes that methane concentration in the upper corner is the lowest.

Obtained results clearly indicate, that both place of displacement of sealing and type of sealing material have significant impact on the methane concentration distribution in the upper corner of longwall.

6. Conclusions
The region of crossing of longwall with ventilation roadway is a place where for methane longwalls one should expect hazardous concentrations of this gas. Particularly an unliquidated part of ventilation roadway is an area where methane is accumulated, forming zone of high methane concentration in the mixture with air. Activation of methane hazard i.e. explosions and inflammation of methane in underground work environment is a major menace to safety of the entire crew and can be cause of many material losses for the mine. For added security, it is necessary to take concrete preventive actions. One of the most effective activities to improve this state is sealing of goaf with caving and mining heading.

Simulation tests were carried out with use of finite volume method. Obtained results clearly indicate, that by a proper selection of degree of sealing of goaf with caving, one can have significant influence on the air stream parameters in the region of upper corner of longwall.

Obtained results clearly indicate that one way of effective improvement of ventilation safety state in mining heading is their proper sealing. Particularly, it is applied to goaf with caving i.e. an area where the highest accumulation of dangerous ventilation factors takes place.

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