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CFD INVESTIGATION OF GOAF FLOW OF METHANE RELEASED FROM UNMINED ADJACENT COAL SEAMS

Hua GUO[1], Johnny QIN[1*] and Qingdong QU[1]

[1] CSIRO Earth Science and Resource Engineering, PO Box 883, Kenmore, QLD 4069, AUSTRALIA
*Corresponding author, E-mail address: Johnny.qin@csiro.au

ABSTRACT

Extracting one coal seam in an underground multiple coal seam mine will lead to methane release from the adjacent coal seams lying over or under the active mining seam due to mining induced stress and pressure relieve. The released methane needs to be effectively drained before it enters the active longwall workings to prevent it from exceeding statutory limit and causing safety and environmental problems. To achieve this it is essential to understand the gas flow pattern and distribution within the goaf after methane is released. This paper presents a CFD investigation on the flow patterns of methane released from both the overlying and underlying coal seams of a longwall panel with a dip angle of 21°. The modelling focused on the gas distribution at the early stage of methane flow starting from the adjacent coal seams. The results indicated that the areas along the longwall goaf perimeter are major pathways of methane flow where high flow velocity and high methane concentration were predicted. Gas drainage boreholes are therefore recommended to be located at these areas. Further modelling of goaf flow with goaf gas drainage boreholes showed that boreholes located on the upper side of the perimeter area perform better than on the down side area in terms of drained methane concentration.

INTRODUCTION

In an underground longwall coal mines with multiple seams, when one of the coal seams is extracted, the adjacent coal seams, lying either over or below the one being mined will be de-stressed, and the pore pressure of the coal matrix will be reduced, leading to gas release from the coal matrix of the adjacent coal seams. The released methane will flow through the strata into the goaf, and may enter the longwall workings. This can cause serious safety and environmental problems. In mining practice, various gas drainage technologies including cross-measured and inseam boreholes, underground gas tunnels excavated above and below working seams, goaf drainage with surface boreholes are used to capture the released methane before it enters the longwall workings (Guo et al 2012).

To effectively capture gas from the goaf, optimisation of the drainage borehole locations is essential. Before determining the borehole locations the most important task is to understand the gas flow pattern and distribution within the goaf. However, due to the inaccessibility of the longwall goaf, the gas flow pattern and gas distribution can not be detected by direct measurement. Computational fluid dynamics (CFD) modelling has been considered a useful approach in simulating the fluid dynamics enabling mining engineers to see the "unseen" happening within the longwall goaf (Karacan et al., 2007; Yuan et al., 2006; Ren and Balusu, 2005). Through the past decade, CFD has been used to simulate the gas migration within longwall goaf areas with the objective of improving gas capture, minimising the risk of spontaneous combustion and developing effective goaf inertisation strategies (Ren and Balusu, 2009; Guo et al. 2012). Different CFD models were developed to simulate various scenarios of ventilation arrangements, gas capture designs and inertisation strategies (Balusu et al, 2002; Wendt and Balusu, 2002; Ren, Balusu and Humphries, 2005). In an attempt to understand the process of spontaneous combustion, a preliminary CFD model of spontaneous heating of coals in a two-panel goaf using a bleeder ventilation system and a stationary longwall face was carried out (Yuan and Smith, 2008).

To provide information for coal mine personnel to optimise the design of goaf gas drainage from overlying and underlying strata, this paper presents an investigation using a 3D CFD model to simulate the gas flow of a longwall goaf. The studied panel has a dip angle (21°) along the longwall face. The gases in the goaf were mainly released from both overlying and underlying coal seams which were de-stressed by mining. The simulation focused on identifying the efficient pathways of gas flow by examining the methane distribution patterns during the early stage of gas release, so as to identify the possible rich gas areas for drainage boreholes to be located. Cases with different drainage schemes were also simulated to study the effect of different drainage borehole configurations on drained methane concentration.

MODEL DESCRIPTION

Geometry

The panel selected for the investigation is the panel 5111(0) of Xieyi mine, at Huainan, located in Southeast China. Figure 1 shows the layout of the longwall panel 5111(0) and ventilation system as well as the relative locations of the three coal seams. The ventilation of the panel is a Y-type system with three entries, two intakes (MG1 and MG2) and one return (TG). The panel is 2000 m long and 220 m wide with a dip angle of 21º along the longwall face. In this study the CFD simulation was applied to the goaf when the longwall face retreated at 500 m from the start line. The seam C10 is the working seam. There are two coal seams C11 and C9 located at 25 m above and 25 m below the active seam respectively. The geometry of the CFD model includes underlying and overlying strata of 50 metres above and below the mining panel. The meshed domain of the CFD model is shown in Figure 2.

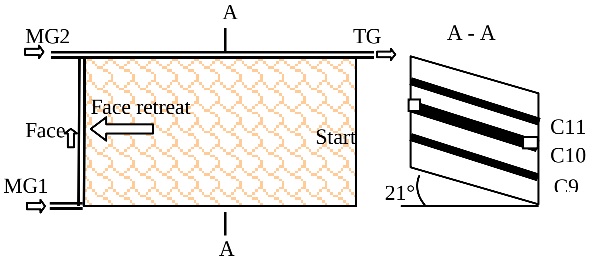

Figure 1: Schematics of the layout of the study longwall panel.

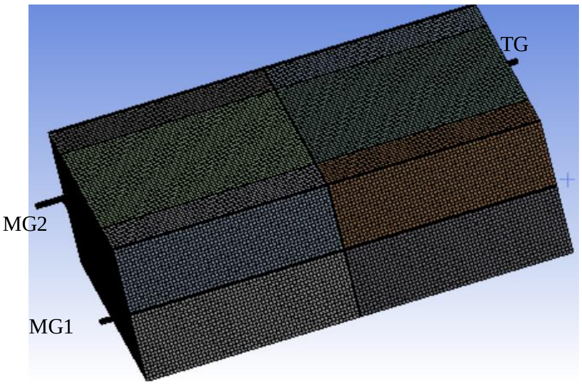

Figure 2: The meshed domain of the CFD model.

Properties of the longwall goaf

The goaf was treated as a porous medium. One of the challenges for modelling goaf gas flows is the determination of the permeability of the goaf. The process of stress redistribution and strata fracturing leads to dynamic changes of permeability. Which is complex as it is not only a function of space, but also time. Previous researchers used empirical relationships to estimate the permeability values based on geomechanical models which simulate the response of rock layers to longwall mining in terms of stress, strain, and fracturing. For example, Smith and his co-workers used the result of a 2D FLAC (Fast Lagrangian Analysis of Continua) model to estimate permeability values for their CFD modelling inputs (Yun, Smith and Brune, 2006; Yuan, and Smith, 2008; Smith and Yuan 2010). In their CFD models the panel was divided into five zones from the margin to the centre with permeability values varying from 5x10^{-12} m^2 to 1x10^{-9} m^2. In addition, they assumed that the permeability remains constant in each of the five zones along the vertical direction.

The method used in this study in determining the distribution of goaf permeability was similar to that used by other researchers. The computer code COSFLOW developed by CSIRO was employed to simulate the geotechnical response to longwall mining and provide the values and distribution of the permeability of the goaf. COSFLOW is a finite element code that enables three dimensional simulation of the complex interaction between rock mechanical response and two-phase fluid flow and thus is able to directly provide the values of permeability. More details about COSFLOW can be found in the paper published by Guo and Adhikary (2009). Before the start of COSFLOW modelling, however, extensive site monitoring of strata stress and deformation using extensometers and strain gages was undertaken to obtain actual data for the calibration of the model. Figure 3 shows an example of the comparison between monitored strata deformation and the corresponding results from the model, indicating a validated model had been reasonably achieved.

Figures 4 and 5 show the modelled permeability changes in this study panel in two sections. The figures indicate that the range of a significant increase of permeability reaches quite a distance to overlying and underlying strata of the mined panel. On a horizontal section above the longwall goaf, the permeability along the perimeter of the goaf is higher than other areas and reduces towards the centre of the panel, forming a series of circular rings as revealed by many researchers (Yuan et al., 2006; Guo et al., 2012). As the vertical distance from the active panel increases, the extent of the increase of permeability becomes smaller, and the circular rings converge. These changes appear in both overlying and underlying strata; however, the permeability increase in the underlying strata is much smaller than that in the overlying strata.

Based on the COSFLOW modelling results, the permeability values applied in the CFD model range from 10^{-12} m^2 to 10^{-7} m^2. In addition, the permeability values in different directions are different. In general, permeability in the horizontal direction is larger than that in the vertical direction. The difference of the permeability values in the two directions increases as the distance from the panel increases vertically, and can be up to 1-2 orders. The permeability distribution was written as a user defined function (UDF) as a zone profile in Fluent and assigned to cell zone of the CFD model.

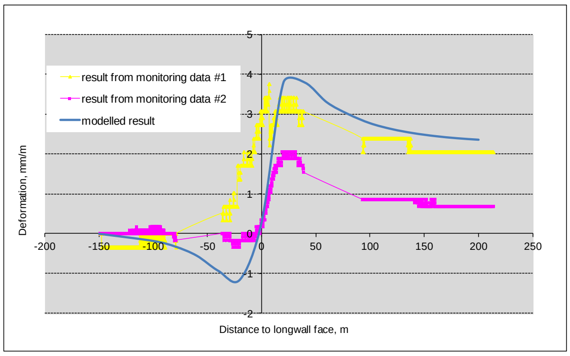

Figure 3: Monitored geomechanical responses due to longwall mining.

Boundary conditions

Boundary conditions for the two intake entries, MG1 and MG2 were set as velocity inlet with magnitudes 1.1 m/s and 0.5 m/s respectively according to the ventilation condition of the panel 5111(0). The return entry, TG, was set as outflow with flow rate weighting of 1. The permeability for the longwall face was adjusted so that the pressure loss from MG1 to MG2 is about 120 Pa. The species transport model was used for two species, i.e. for air and methane. Four methane sources were assumed including the face, the leftover coal of the mined seam, and the two overlying and underlying adjacent seams C11 and C9. Total methane emission rate was assumed to be 40 m^3/min, with 20% from the face and 20% from the leftover coal and 30% from each of the overlying and underlying seams. These sources were written in a UDF file to be assigned to the relevant cell zones in the CFD model.

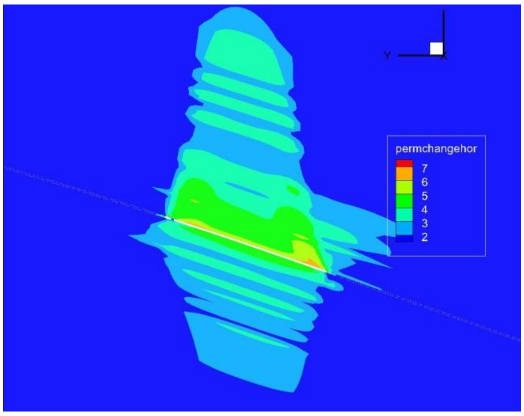

Figure 4: Permeability change on a vertical section modelled by COSFLOW.

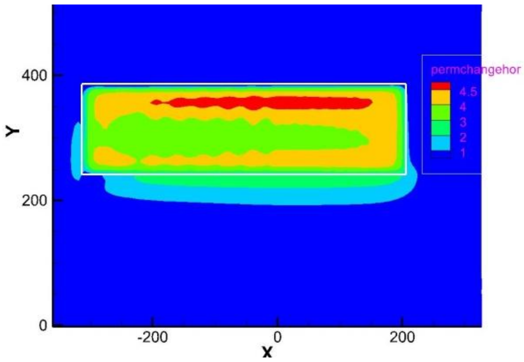

Figure 5: Permeability change on a horizontal section modelled by COSFLOW.

VELOCITY AND METHANE DISTRIBUTIONS

Model was first run as transient flow with zero initial methane concentration over the domain to investigate the process of methane appearing and accumulation in the goaf.

Flow velocity distribution

Although the boundary conditions of inlet and outlet and methane emission rate were assumed unchanged with time, the velocities in the modelled domain may change with time due to the accumulation of methane and the gravity effect. However, through comparing the velocity contours at different flow times, it was found that the velocity distribution changes were so small that one can consider the velocity distribution patterns unchanged. Figures 6 and 7 show the typical velocity contours on a vertical section and a section parallel to the longwall panel.

It is seen that velocities near the periphery of the panel are much higher than those in the centre areas. The contours form circular-like patterns which are consistent with the permeability patterns calculated from COSFLOW as shown in Figures 4 and 5.

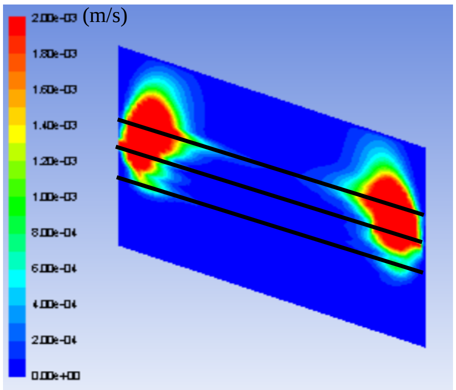

Figure 6: Velocity contours on a vertical section 250 m behind the face.

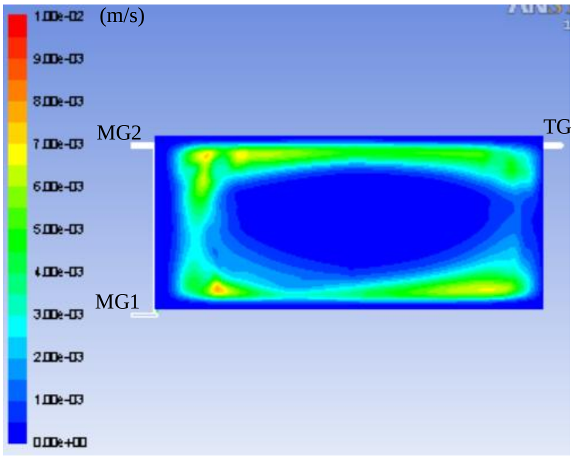

Figure 7: Velocity contours on a section 30 m above and parallel to the longwall panel.

Methane distributions

As methane releases from coal seams, it flows and accumulates within the goaf. During the process of accumulation the methane concentration at different position varies with time. Figures 8, 9 and 10 display the methane concentration changes as time on a vertical section 250 m behind the longwall face. It can be seen that methane appears first at the locations within and close to coal seams. As time goes on, the range of strata containing methane expands and the concentration of methane increases.

The pathways of methane flow can be reflected from the distribution of methane concentration at a level of non-coal stratum. Figure 11 to Figure 13 demonstrate the process of methane appearing and accumulating on a section of 30 m above the working seam, which is 5 m above the overlying coal seam C11. From the figures it can be seen that methane appears first at the areas close to the margin area of the goaf which is near the longwall face. As time goes on, more and more methane comes in, and the area of strata containing methane is expanding. It is noted that the areas where methane first appears and accumulates are coincident with those of high velocity areas.

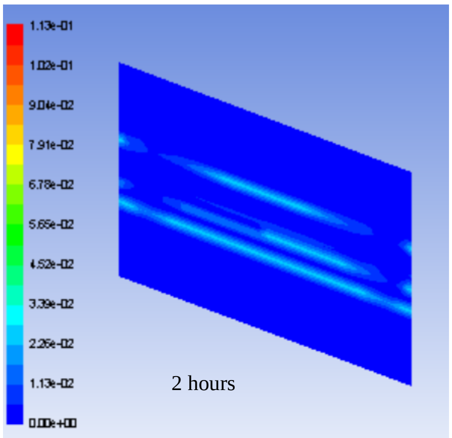

Figure 8: Methane concentration on a vertical section 250 m behind the longwall face after running 2 hours.

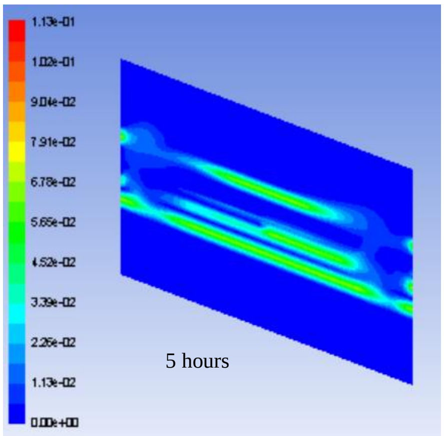

Figure 9: Methane concentration on a vertical section 250 m behind the longwall face after running 5 hours.

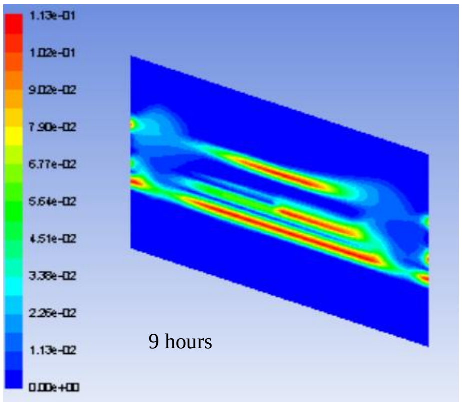

Figure 10: Methane concentration on a vertical section 250 m behind the longwall face after running 9 hours.

Since the porosities at the perimeter areas are also larger than the other areas, as the velocity distribution does, the volume of methane contained in these areas should be larger than that of the other areas. Thus these perimeter areas may be considered as the methane-rich zones of the longwall goaf.

Another note is that methane concentration on the upper side is higher than that of the downside. In addition, the migration trend of methane is from the downside upwards the upper side. This is believed to be partially caused by the buoyancy effect due to the gravity as the density of methane is less than that of the air. The fact that the permeability in horizontal direction is larger than that in vertical direction also makes the methane move from the downside towards the upper side easier.

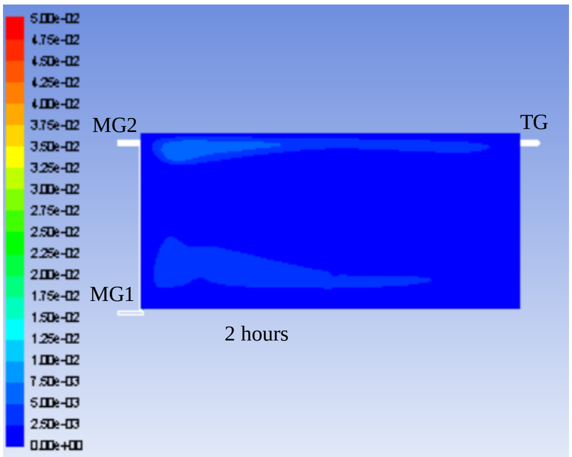

Figure 11: Contours of methane concentration on a section 30 m above the mined seam after running 2 hours.

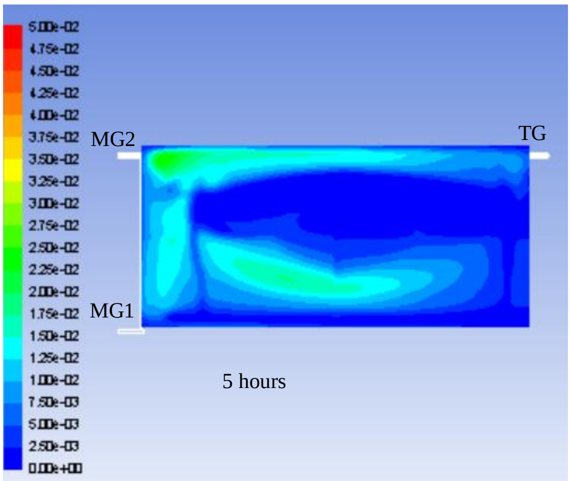

Figure 12: Contours of methane concentration on a section 30 m above the mined seam after running 5 hours.

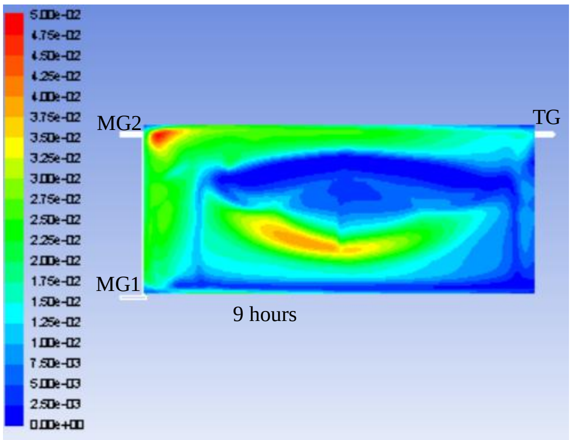

Figure 13: Contours of methane concentration on a section 30 m above the mined seam after running 9 hours.

Effect of borehole location on drainage gas concentration

To investigate the effect of different locations of drainage borehole on drainage gas concentration, four boreholes, B1, B2, B3 and B4 were added to the model, as shown in

Figure 14. Simulations were run under the assumption of steady state flow, to simulate the situation that sufficient time had been allowed for coal seam gas to release. The boundary conditions for the borehole exits were set as mixture flow rate of 30 m^3/min. For the purpose of comparison, the case of without drainage borehole on operation was also simulated.

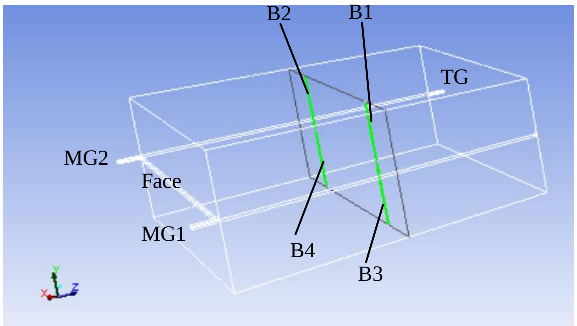

Figure 14: Schematic representation drainage boreholes in CFD modelling.

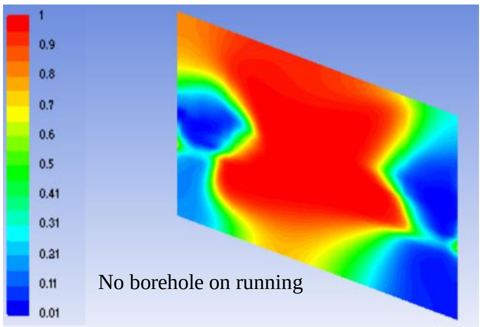

Figure 15: Methane concentration on a vertical section 250 m behind the longwall face without borehole drainage.

Figure 15 is the methane contours on the vertical section 250 m behind the longwall face. It is seen that methane concentration on the areas close to ventilation tunnel is lower than the centre areas of the goaf. This is due to the ventilation air ingression from the two intake entries into the goaf leading to dilution of the methane. Figure 16 is the methane concentration contours of the case of with roof drainage boreholes of B1 and B2 on running. While the methane concentration on the floor strata does not change much, significant reduction of methane concentration happens in the roof strata where the drainage boreholes were on operation. Figure 17 displays the methane concentration contours in the operating roof drainage boreholes. It is seen that the methane concentration at the exit of the borehole B2 reaches 56%, much higher than at the exit of B1, indicating upper side borehole performs better than downside borehole in terms of capturing high concentration methane.

Results of the case with floor boreholes on running are shown in Figures 18 and 19. Contrast to the case with roof drainage boreholes on running, the reduction of methane concentration happens mostly on the floor strata where the drainage boreholes B3 and B4 located. Methane concentration at the borehole exit is 16% and 30% for B3 and B4 respectively as shown in Figure 19. Comparison of Figure 17 and Figure 19 indicates that boreholes drilled to roof strata can capture gas with higher methane concentration than those drilled to floor strata. Methane concentration at borehole exit for the four boreholes is listed in Table1.

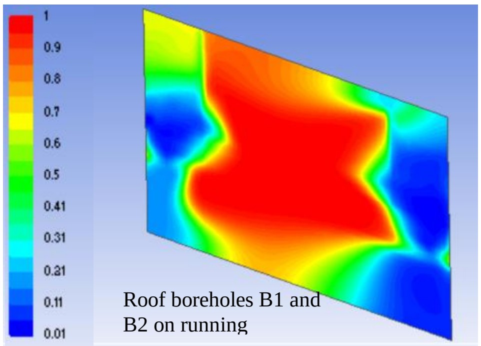

Figure 16: Methane concentration on a vertical section 250 m behind the longwall face with 2 roof borehole drainages.

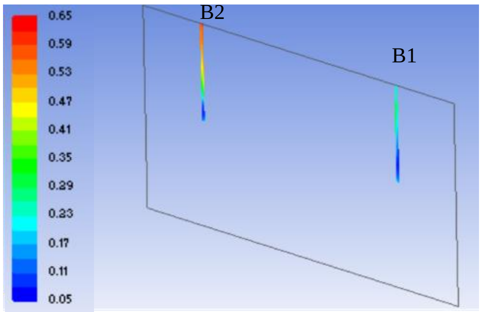

Figure 17: Methane concentration in the 2 roof drainage boreholes.

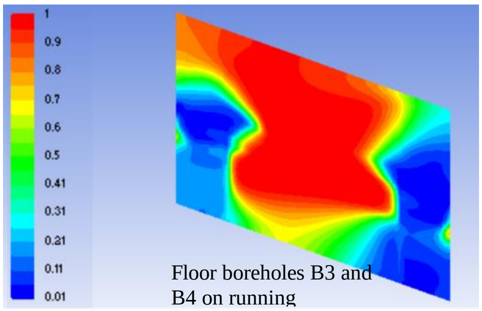

Figure 18: Methane concentration on a vertical section 250 m behind the longwall face with 2 floor borehole drainages.

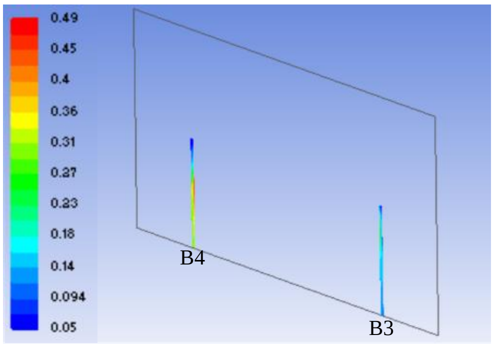

Figure 19: Methane concentration in the 2 floor drainage boreholes.

Borehole	B1	B2	B3	B4
End position of borehole	Roof 30 m	Roof 30 m	Floor 30 m	Floor 30 m
Drainage mixer rate	30 m^3/min	30 m^3/min	30 m^3/min	30 m^3/min
Methane concentration	29%	65%	16%	30%

Table 1: Comparison of drained methane concentration from different boreholes.

CONCLUSION

The methane flow pattern from the adjacent coal seams of a longwall panel into the goaf was investigated using a CFD model run as transient flow. The results show that the released methane migrates first through the perimeter of each level of the goaf and then gradually expands to the central area. The perimeter areas of the goaf have higher gas flow velocity and methane concentration than the other parts of the goaf, forming major pathways and rich zones of methane within the goaf. It is therefore suggested that goaf gas drainage boreholes be located at this area to improve drainage in terms of capturing higher methane concentration and flow rate.

Simulations under the condition of steady state flow indicate that methane concentration on the upper side of the goaf is higher than that on the downside. Simulations with gas drainage borehole running further reveal that boreholes located on the upper side of the goaf can capture gas with higher methane concentration than that located on the downside.

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