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CFD study of the effect of face ventilation on CH_4 in returns and explosive gas zones in progressively sealed longwall gobs

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Synopsis

The main purpose of coal mine ventilation design is to provide a sufficient quantity and quality of air to the workers and to dilute methane and other contaminants. It is generally perceived that additional air along the longwall face will improve methane dilution at the face and in the tailgate. However, computational fluid dynamics (CFD) modelling efforts at the Colorado School of Mines (CSM) under a National Institute for Occupational Safety and Health (NIOSH) funded research project have found that higher flow velocities along the longwall face will increase the pressure differential between the gob and longwall face and allow more methane to be swept from the gob into the active face and tailgate area, thereby diminishing the dilution effect. Increased pressure along the headgate side also allows more oxygen to ingress into the gob area, thereby increasing the amount of oxygen available to form explosive methane-air mixtures in the gob and to support spontaneous combustion of the coal. In this paper, a parametric study is presented to discuss the effect of face air quantity on methane concentrations in the tailgate and formation of explosive gas zones (EGZs) in the gob. Counter to conventional wisdom, increased air quantities at the longwall face may increase the explosion hazard as they result in increased EGZ volumes in the gob, along with increased methane quantities in the tailgate return.

Keywords
computational fluid dynamics, explosive gas zones, spontaneous combustion, gob ventilation boreholes.

Introduction

Longwall mining is an underground mining method that maximizes safe coal production from coal beds that do not have major geological discontinuities. In the western United States, the majority of underground-mined coal is produced through longwall mining. The initial step in developing a longwall mine is to drive development entries around the panel using the continuous miners, leaving behind a solid block of coal with dimensions ranging from 900–6 000 m (3 000 –20 000 ft) in length and 300–500 m (1 000–1 500 ft) in width. Once panel development is complete, longwall machinery is placed along the face of block and longwall mining begins. A continuous flow of fresh air is provided to the face and working sites by the ventilation system. The intake side of the longwall panel is referred to as the headgate, and the ventilation return is through the tailgate. During longwall mining operation, the coal is continuously cut by a shearer and extracted via an armoured face conveyor. Following extraction, the shield roof supports are advanced. As the shields move forward along the panel, the immediate roof is allowed to collapse into the void behind the shields. The collapse of roof rock forms a pile of rock fragments known as the gob. The passing longwall face also disturbs the strata overlying the gob, leading to subsidence.

Methane ignition, explosion, and spontaneous combustion ('spon-com') are major safety hazards in underground longwall coal mines. Safety systems to monitor and control these hazards include; ventilation design, air quality monitoring systems, methane degasification, gob ventilation boreholes, and inertization of the gob. Ventilation systems must be designed to provide sufficient air to the face for workers and to dilute hazardous gases like methane to acceptable levels. The face air can enter into the gob by leaking past the face support shields and may form explosive mixtures as it combines with methane present in the gob. The methane-air mixtures in the explosive range are called explosive gas zones and present an explosion and fire hazard. As the Upper Big Branch (UBB) disaster in 2010 has shown, methane explosions can also lead to coal dust explosions, which can spread to a larger area underground. The fatalities caused by some major methane fires and explosions in underground coal mines of the United States between 2000 and 2010 are shown in Table I. Goodman *et al.* (2008) summarized the

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Table I

Methane ignition accidents in US underground coal mines from 2000 to 2010 (Saki *et al.*, 2015a)

	Methane ignition accidents	
Year	**Underground coal mine**	**Fatalities**
2000	Willow Creek Mine	2
2001	Jim Walter Resources, No. 5 Mine	13
2003	McElroy Mine	3
2006	Sago and Darby Mine	17
2010	Upper Big Branch Mine	29

following recent methane ignition accidents. In July 2000, a methane gas explosion occurred in the gob at Willow Creek mine, which caused two fatalities and eight serious injuries. In September 2001, an explosion accident occurred at Jim Walter Resources No. 5 mine in Alabama, though not in the gob, which resulted in 13 fatalities and 3 injured workers. In 2006, an explosion in a sealed, mined-out area at the Sago Mine in West Virginia caused 12 fatalities and 1 injury. In May 2006, a similar accident at the Kentucky Darby Mine resulted in 5 deaths. The most recent explosion at Upper Big Branch in 2010 killed 29 miners. The investigation report by Page *et al.* (2011) revealed that methane from the gob was ignited by the shearer cutting near the tailgate and set off a coal dust explosion which spread through almost 50 miles of mine entries.

Current methane monitoring technologies do not provide information on the gas distribution and flow patterns inside the gob areas. In order to obtain information about gas compositions in the gob, the authors modelled the gas flows inside the gob using computational fluid dynamics (CFD). CFD modelling can predict the gas flow patterns inside the gob and the formation of EGZs. It can also determine the volume and locations of EGZs and oxygen ingress into the gob.

Previous CFD modelling research

Various researchers have used CFD to model gas flows in longwall gobs under different ventilation schemes. Ren, Balusu, and Humphries (2005) used CFD modelling of longwall gobs and concluded that reduction in the face air velocity on the intake side of the goaf will help to reduce the risk of spon-com. Krishna, Balusu, and Manoj (2012) used CFD to study the effect of buoyancy on methane gas distribution in the tailgate region and concluded that a back return system was helpful in reducing the tailgate methane concentration level to below 1%. Brune and Sapko (2012) used CFD to analyse the ventilation and potential methane accumulation and mixing patterns in the tailgate corner area, and recommended keeping the immediate longwall tailgate entry open at least to the nearest inby crosscut so that positive ventilation is maintained inby the face to dilute and carry away any methane released behind the shields.

Researchers at the Colorado School of Mines, under a project funded by the National Institute for Occupational Safety and Health (NIOSH), have modelled various longwall panels and ventilation configurations using the CFD software FLUENT® by ANSYS. Marts *et al.* (2013) determined that a lower face ventilation quantity will reduce the size of EGZs in longwall gobs. They also found that nitrogen injection is more effective from the headgate side than it is from the tailgate side, and that there is a point of diminishing returns where additional nitrogen injection will no longer reduce EGZ volume. Marts *et al.* (2013) recommended a back return arrangement on the tailgate side, which is effective in pushing the tailgate EGZ away from face and reducing the likelihood of ignitions near the face due to the shearer cutting hard rock. Marts *et al.* (2014) also reported that the nitrogen injection and reduction in the face air velocity can effectively control spon-com risk in the sealed gobs. Gilmore *et al.* (2014a) concluded that a bleeder ventilated gob will carry a contiguous explosive fringe on all sides surrounding the gob. Marts *et al.* (2014) found that headgate nitrogen injection may form a ’dynamic seal’ separating the oxygen-rich face zone from the methane-rich interior gob without forming an explosive fringe in the case of progressively sealed gob. In this paper, the results of modelling studies with varying quantities of air at the face to dilute the tailgate methane are presented. Also, the communication of gob gases with face air and tailgate return, and the performance of gob ventilation boreholes (GVBs) under varying face air quantities, are analysed.

CFD model creation

The CFD model grid was created using ventilation and air quality data collected from two cooperating mines in the western United States. The collected data consisted of mine layouts, geometric dimensions, lithology, overburden caving characteristics, ventilation operating conditions, and gas concentration measurements. The CFD model panel is 314 m (1030 ft) in width and 39 m (128 ft) in height to account for the caved and fractured zone above the coal seam. Gob ventilation boreholes (GVBs) extend into the fractured zone and terminate at 18 m (60 ft) above the top of coal seam. GVBs are 18 m (60 ft) away from the gateroads, with the first GVB being located about 66 m (220 ft) inby the face. The spacing between the GVBs is 60 m (200 ft). A vertical cross-section of the model geometry is shown in Figure 1. The communication of flow between the gob and the face is modelled through shield leakage.

Ventilation layout

The CFD model was constructed with a ‘U’ ventilation design for a progressively sealed panel, as shown in Figure 2. In the United States, regulations require the use of a bleeder system (Mine Safety & Health Administration, n.d). Exceptions may be granted if the coal has a tendency to spontaneously combust. Many western US coals are prone to spon-com and several mines in this area use progressive sealing (also referred to as bleederless panels) to reduce the oxygen ingress into the gob. This is accomplished by progressively sealing the headgate side crosscuts as the panel advances. Gilmore *et al.* (2014b) concluded that U-ventilation is an effective method to limit oxygen ingress into the gob to prevent spon-com. The fresh intake air enters the longwall face through the headgate, travels across the face, and leaves through the tailgate.

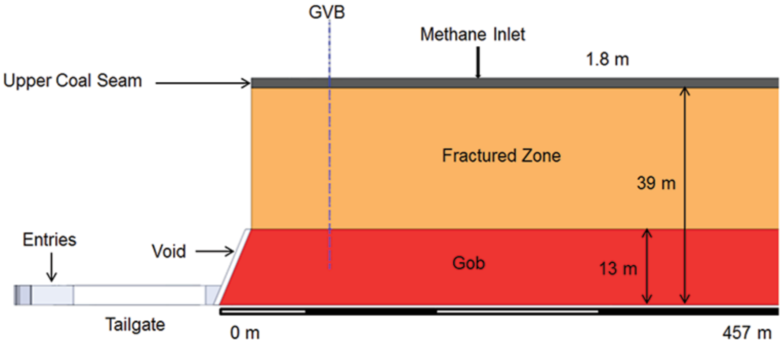

Figure 1—Vertical cross-section of model geometry (Saki, 2016a)

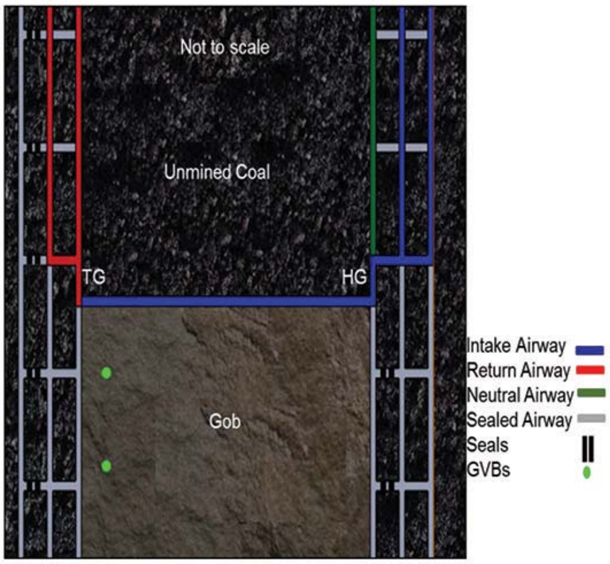

Figure 2—Progressively sealed, U-type ventilation design (Saki *et al.*, (2015b)

Boundary conditions

In the CFD modelling efforts, the longwall face ventilation air quantity was varied from 23 m^3/s (50 000 cfm) to 61 m^3/s (130 000 cfm), with nitrogen injection on both the headgate and tailgate of 0.19 m^3/s (400 cfm). The GVBs were operated at a flow rate of 0.17 m^3/s (350 cfm). A rider coal seam 40 m (130 ft) above the mined horizon was modelled as methane inlet, based on the actual stratigraphy of the cooperating mine. The methane inlet amount for the model was determined from mine measurements of methane released by the ventilation systems and GVBs. The methane liberation rate used for the 460 m (1500 ft.) panel length is 0.5 m^3/s (1040 cfm). The gob permeability is in the range of $2.0*10^{-7}$ to $5.1*10^{-6}$ m^2 and the porosity is 14 to 40%, based on geomechanical modelling using actual mine lithology, shield loading information, as well as final and dynamic subsidence data (Marts *et al.*, 2014b). More information about meshing, model set-up, grid independence, turbulence, convergence, and solution is presented in a previous publication of CSM coal mine ventilation and safety research group (Gilmore *et al.*, 2015).

Explosion hazard characterization

The explosive potential for the mixtures of methane and air is presented using a colouring scheme based on Coward's triangle (Coward and Jones, 1952), as depicted in Figure 3. There are four distinct regions: the explosive region (red), a fuel-rich inert region that can become explosive when fresh air or oxygen is added (yellow), an inert region where no explosive composition is possible (green and dark green), and a fuel-lean inert region (blue). The orange colour denotes an arbitrary, near-explosive zone. Worrall *et al.* (2012) developed an algorithm as a user-defined function (UDF) in FLUENT to correlate the methane-air mixtures with these colours. The contour plots for the plan view of the model are shown so as to visualize the EGZs in a plane at a height of 1.5 m (5 ft) above the mine floor, which is approximately in the middle of the coal seam height.

Model validation

The authors validated the model predictions with the gas measurements conducted by the mine. The cooperating mine used a tube bundle gas analyser system that allowed for measurements along the fringe of the gob. The mine also provided the data for measurements of gases through seal sampling tubes and from manual readings at the face.

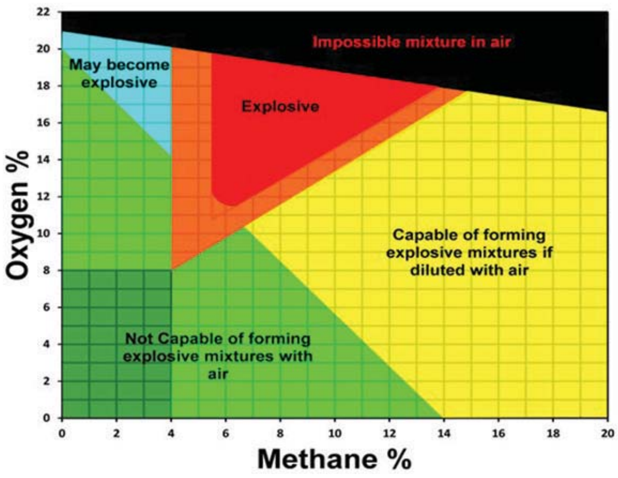

Figure 3—Modified Coward's triangle (Saki *et al.*, 2016b, after Coward and Jones, 1952)

Additionally, discussions with mine personnel were used to validate the results. Oxygen ingress in the model was compared with an actual mine as shown in Figure 4 at actual operating conditions. Figure 4a shows the 12% oxygen contour plot from actual mine data, while Figure 4b shows the oxygen contour plots from the model. The model predictions agree with oxygen measurements taken in the mine. The general results of the CFD models agreed with operator experience. The methane concentration at the tailgate return (0.5%) matched with the mine measurements. The methane concentration of gob ventilation boreholes exhaust predicted by the models also matched with the GVBs methane quality at mine. According to the operator, methane enters the face primarily at the tailgate corner as shown by the models in Figure 8. The operator also reported low oxygen concentration behind the shields inby the tailgate corner, which matched the models results shown in Figure 4b.

Discussion

Figure 5 shows the explosive mixture plots on the left and oxygen ingress plots on the right. All four cases use nitrogen injection of 0.19 m³/s (400 cfm) on both the headgate and tailgate sides. Two GVBs are operating on the tailgate side. Figure 5a shows gas mixtures at a face air quantity of 33 m³/s (70 000 cfm) and Figure 5b shows the results for a face air quantity of 61 m³/s (130 000 cfm). In Figure 5a, a yellow (fuel-rich, oxygen-deficient) zone is visible behind the shields near the tailgate corner. If the oxygen content of this yellow zone increases, it will be capable of forming an explosive mixture. Figure 5a also shows that the nitrogen injection from the headgate (dark green) forms a separation between the oxygen-rich zone near the face and the methane-rich zone in the centre of the gob. Figure 5b shows that with a higher quantity of air on the face (61 m³/s; 130 000 cfm), more face air ingresses into the gob and forms an explosive mixture, visible as a narrow red fringe between the green and yellow areas. The explosive zone extends behind the shields and presents an immediate fire and explosion hazard. The oxygen plots in Figure 5c and Figure 5d show that with 33 m³/s (70 000 cfm) of air on the face, oxygen ingress into the gob is low, whereas with 61 m³/s (130 000 cfm) of air flow on the face, the oxygen ingresses much deeper into the gob. If the coal is present and has a spon-com propensity, such deep oxygen ingress could cause a fire, which would also present an ignition source for the EGZ. In all cases of face air variation from 23 m³/s (50 000 cfm) to 61 m³/s (130 000 cfm), the total EGZs

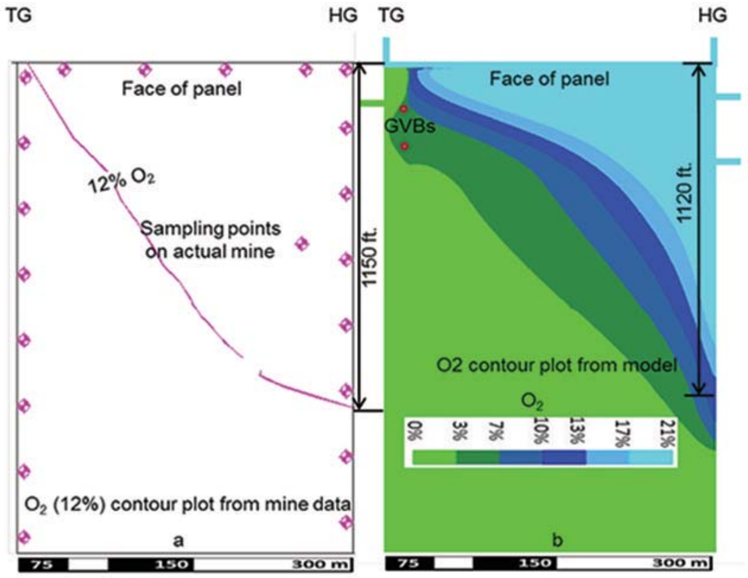

Figure 4—Validation of CFD model predictions of oxygen concentration profiles with oxygen measurements from a mine

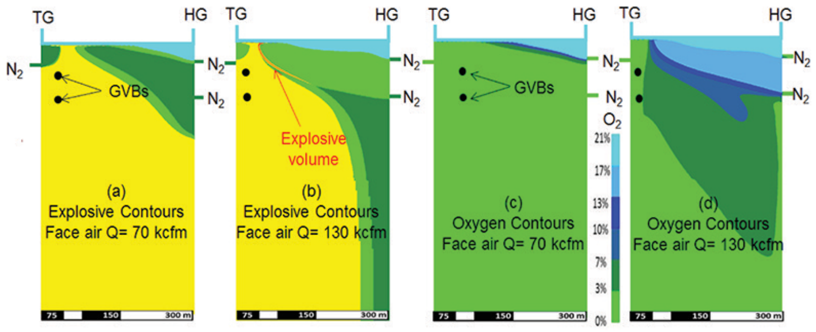

Figure 5—Contour plots of explosive gas and oxygen ingress

volume increased linearly, as shown in Figure 6. It should be noted that the yellow zone, while not explosive, still presents a fire hazard, as fuel-rich mixtures of methane and air can burn with a diffusion flame. Most of the deeper gobs contain little or no oxygen, as shown in oxygen contours plots in Figure 5b and Figure 5c.

Explosive gas zones (EGZs) and methane in tailgate returns

The authors documented the relative volume of explosive mixtures and concentrations of methane in the tailgate return as a function of varying face air quantity. Normally, one would expect linear dilution of the tailgate and face methane with increased face air quantities. However, Figure 6 shows that there is no significant reduction of the tailgate methane concentration (red line) above a certain face air quantity (about 33 m^3/s; 70 000 cfm in this case). Figure 6 shows that the EGZ volume (blue line) in the gob increases with increasing face air quantity. This phenomenon is explained as follows. As the face ventilation quantity is increased, a higher pressure differential is created between the face and the gob and more air (oxygen) will migrate into the gob through the gaps between the shields. Oxygen ingress into the gob will enhance the formation of explosive mixtures. Where the coal has a high propensity for spontaneous combustion, the oxygen ingress may also increase the spon-com potential. As shown in Figure 5b, if that EGZ is located just behind the face, small changes to the gob atmospheric pressure due to a drop in barometric pressure or a roof fall could push the EGZ into the face area.

Gob communication with face and tailgate return

The authors further investigated the phenomenon that increased air flow along the face will not lead to a proportional dilution in tailgate methane concentrations, as shown in Figure 6. There are two related phenomena occurring at two different locations along the longwall face. An increase in pressure as the flow enters the active area will force more oxygen into the gob, but as the flow is developed along the longwall face, the higher velocity causes a greater pressure drop, allowing methane to enter the active face further downstream from the headgate towards the tailgate side. Figure 7 shows that increasing the face air quantity increases the volumetric flow of fresh air into the gob on the headgate side (blue line). This air ingress or leakage flow sweeps increasing amounts of methane from the gob towards the face and into the tailgate. The red line shows the concentration of methane in the flow from the gob towards the face. The trend lines show a near-linear relationship between the face air quantity and the air and gas exchange phenomena in the gob; this observed trend provides insights as to why the concentration of methane does not drop further after a certain face air quantity. The path lines of air flow in the gob are shown in Figure 8, which confirms the flow into and out of the gob towards the tailgate.

Gob ventilation borehole performance

The model contains two GVBs on the tailgate side that are operated at 0.17 m^3/s (350 cfm). The concentration of methane in the GVB exhaust from the modelling predictions is plotted in Figure 9. Methane concentration in both GVBs is near 100% at face air quantities of 33 m^3/s (70 000 cfm) or below. Since GVB 1 (red line) is located near the nitrogen injection point on the tailgate side crosscut, some nitrogen ends up in the GVB, reducing the methane concentration slightly. As the face air quantity is increased above 33 m^3/s (70 000 cfm), the methane concentration in the GVBs decreases due to the face air ingressing into the gob and moving into the GVBs. As the face air quantity is increased, the GVBs start exhausting more air and the methane concentration in the exhaust subsequently decreases. GVB performance provides additional evidence that higher face air quantities lead to deeper oxygen penetration into the gob.

Summary and conclusions

The following conclusions are based on observed trends in the above CFD parametric study on face ventilation.

- ➤ By increasing the quantity of air on the longwall face, additional air from the face is pushed into the gob near

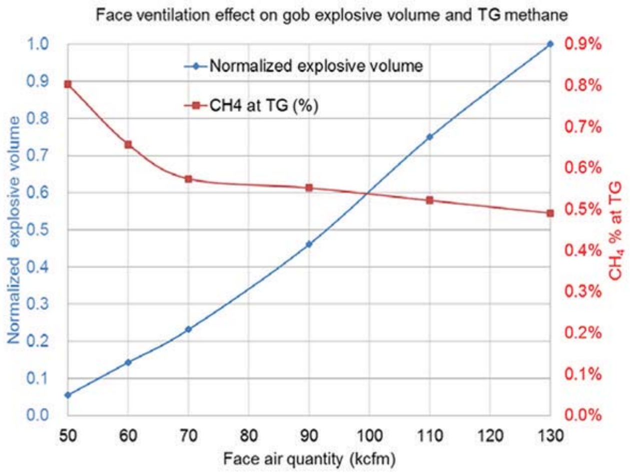

Figure 6—Explosive gas zones volume and CH_4 concentrations for varying face air quantities

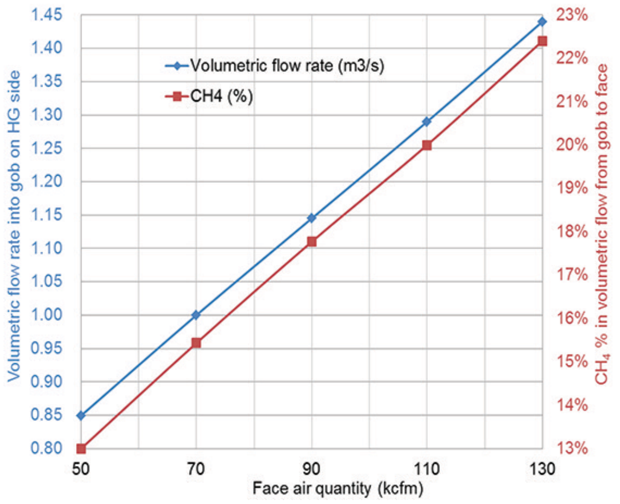

Figure 7—Flow from face to gob and gob to face

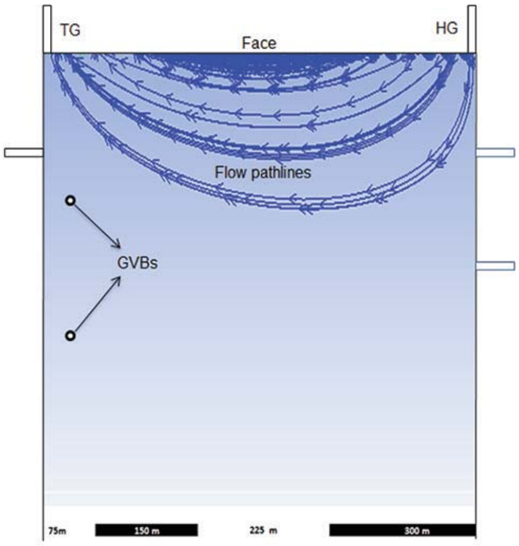

Figure 8—Flow pathlines in the gob

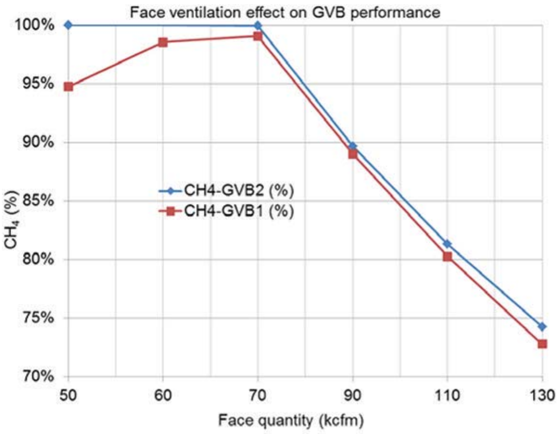

Figure 9—Gob ventilation boreholes performance

the headgate side. In progressively sealed panels, this fresh air ingress tends to sweep methane from the gob into the tailgate. Hence an increased face air quantity does not result in linear dilution of methane on the face. As the face air quantity is increased, a point is reached where the reduction in the tailgate methane concentration becomes insignificant

- As fresh air from the face ingresses into the gob, the volume of EGZs and the explosion hazard increase
- Ingress of more air and oxygen from face into the gob can lead to spontaneous combustion hazards
- Air ingress into the gob may decrease the effectiveness of gob ventilation boreholes.

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