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Optimization of gob ventilation boreholes design in longwall mining

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ABSTRACT

Gob ventilation boreholes (GVBs) are widely used for degasification in U.S. longwall coal mines. Depending on geological conditions, 30–50% of methane can be recovered from longwall gob using GVBs. A NIOSH funded research at the Colorado School of Mines confirmed that GVBs can efficiently reduce methane at the face. However, GVBs can also draw some fresh air from the face and create explosive gas zones (EGZs). Explosive gas mixtures may be formed in gob areas due to the increased ingress of oxygen from GVBs. It is critical to identify the locations for GVBs for maximizing extraction of methane and minimizing hazards of explosion. This study analyzes the effect of operating parameters and design of GVB on methane extraction, EGZs formation, and face and tailgate methane concentrations. Methane extraction, formation of EGZs, and concentration of methane in working areas are significantly impacted by various factors. These factors include the distance of work face and tailgate from GVBs, diameter of GVBs, vacuum pressure of wellhead, GVB distance from the roof of the coal seam, and number of operating GVBs in a panel. Computational fluid dynamics (CFD) evaluations suggest optimal design and operating parameters of GVBs that can contribute to maximum benefits with minimum risks.

1. Introduction

Based upon the presence of toxic and hazardous gases like CO_2, CO, and CH_4, coal mines are considered gassy. Gases move in gob areas and working faces from the rider seams that lie above or below the mined coalbeds. In longwall coal mines that have high methane emissions, concentrations of methane in working zones are usually reduced to the statutory levels by supplying sufficient ventilation and adopting additional methane control measures. Methane emissions may come from adjacent coal seams, the active longwall face, roof and floor strata, coal on the conveyers, and remnant coal in the gob area. Methane hazards are controlled by employing various drainage and dilution techniques or their combination. These techniques include the degasification of coalbeds, dilution of face air by ventilation, injection of nitrogen into the gob area and gob ventilation boreholes (GVBs). Longwall face ventilation alone can only handle emission of methane to a certain level. Additional methane control measures are needed when emission of methane exceeds from the face ventilation capacity. Among these additional control measures, drilling of vertical or horizontal boreholes in the coal seams and GVBs in gob area are commonly adopted practices. Usually GVBs are drilled from surface into the gob area ahead of mining. Whenever GVBs are intercepted by the advancing longwall face, the gob begins to form, and methane production starts from the boreholes. In order to maintain safer working in the mine, controlling GVBs performance is a critical parameter. Multiple factors dictate the performance of GVBs. These factors include the length and diameter of slotted casing, depth of casing above the coal seam being mined, vacuum pressure of the wellhead, caved-fractured zones' permeability, and varying air quantities [1].

Methane gas from the gob area and the fractured zone above the gob can be removed by GVBs, as shown in Fig. 1. Generally, GVBs are drilled within 10–30 m above the coal seam into the fractured zone, but not into the caved area. This is done to avoid air entrance from the face and bleeder entries into the gob area. GVBs are usually completed with a 60 m slotted pipe casing at the bottom [2]. The wellhead vacuum pressure is applied to ventilation boreholes by installing vacuum pumps known as exhausters or blowers [3]. The vacuum creates a negative pressure zone which captures the methane and prevents it from entering the underground workings. These GVBs work effectively only if these are drilled very close to the caved zone, as shown in the schematic representation of longwall coal mining and GVB operation over a longwall coal panel in Fig. 1.

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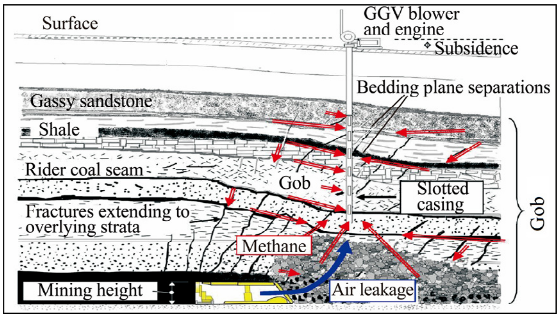


Fig. 1. Schematic of longwall mining with shearer, extending fractures in superimposing strata, separation of bedding planes, subsidence and potential methane flow paths (red arrows) and air leakage from the face, GVB producing gas (after [4]). Note that GGV is the gob gas venthole.

Various numerical modeling efforts and experimental studies have been performed to design, evaluate, and optimize GVBs performance. The U.S. Bureau of Mines (USBM), the NIOSH, Office of Mine Safety and Health Research (OMSHR), and several independent researchers have studied GVBs. The USBM evaluated vertical boreholes for assisting degasification of longwall gobs in the Kittanning coal bed at Bethlehem Mines Corporation's Mine No. 33, where methane was extracted through surface boreholes using wellhead vacuum pumps [4]. Increase in daily coal production was recorded by reducing concentrations of methane in the return airways [4]. Other longwall gob degasification experiments were conducted by the USBM using surface ventilation boreholes in the Lower Kittanning coalbed in central Pennsylvania, where it was reported that the methane level in the return entries dropped by 75% after the first drainage borehole was intercepted and started production [5]. The USBM conducted an experimental study in lower Kittanning coalbeds regarding improving GVBs performance [6]. Researchers reported an 80% higher methane production for GVBs placed near the gate roads as compared to GVBs placed along the center line of the longwall panel [6].

Xue and Balusu [7] studied the process to capture gas from the longwall gobs in a gassiest Australian mine. They monitored methane in real-time and conducted computational fluid dynamics (CFD) modeling efforts of the gob. The methane emissions from the longwall panel were decreased from 1.500 to 0.375 m^3/s with the help of GVBs. Xue and Balusu recommended to place GVBs near the edges of the panels while maintaining a minimum distance from the gate roads so that the GVBs would not draw ventilation air [7]. Balusu et al. [8] presented findings on gob gas drainage in longwall and control measures for extremely gassy mines. The researchers concluded that GVBs provide lowest cost and highest capacity option for the drainage of gob gas, and further recommended that GVBs should be bored at 30–70 m from the gate roads based upon the caving characteristics of gob. They also recommended to design a ventilation system that minimized fresh air or oxygen entering the gob. This can be accomplished by immediately sealing-off all the cut-throughs behind the face, which improves overall gas drainage efficiency.

The mines in the Pittsburgh coalbed have been the subject of extensive modeling studies for methane drainage and GVBs. Karacan [3] carried out an experimental study on longwall gob gas reservoirs and GVB production performance using well test analysis at multiple drawdown rates. In his study, wellhead gas production rates and pressures were examined for six GVBs in contiguous longwall panels after and during mining. Karacan's study showed that well test and reservoir analysis methods can determine the permeability of gob around GVBs, their radius of influence and predict the flow efficiencies of GVBs [3]. A geomechanical study to determine the gob permeability distribution and its application to methane reservoir modeling of longwall coal mines was done by Esterhuizen and Karacan [9]. Fast Lagrangian analysis of continua in three dimensions ($FLAC^{3D}$) was used for Geo-mechanical modeling. A two-stage approach was used to simulate complex process of methane emissions and flow by combining the output of geomechanical models with reservoir models [9]. Karacan et al. [10] applied reservoir modeling techniques for evaluating and optimizing methane control systems in longwall operations. Their research results indicated that an increase in casing diameter of GVB increased cumulative methane production and slightly decreased methane concentrations. The research also demonstrated more methane production with longer slotted casing. The setting casing depth played an important role relative to the concentration and volume of captured methane. Research indicated that a protruded slotted casing into the caved region will decrease methane production from GVBs by about 30%. Karacan et al. also reported that moving the GVB away from the tailgate and towards the centerline would reduce gas drainage capability [11].

Researchers at the USBM conducted an experimental study to improve the performance of gob ventilation boreholes. They monitored 61 gob ventholes over a period of seven months for five longwall panels at Lower Kittanning coal bed. The mine operator placed five holes near the centerline on a 216-m-wide panel and seven holes near the margins of the panel located at 16.8–59.4 m from panel gate-roads. After seven months of monitoring, they reported that near-margin holes produced 80% more methane than centerline holes. Diamond et al. [12] reported higher permeability near the margins of panel where strata was in tension and supported by pillars. They also concluded that high permeability was the reason for higher production of near-margins holes. The centerline strata was under compression and it reduced the permeability of gob over the time, and most of the holes stopped production even before the completion of seven-month monitoring period because of very low permeability [12].

A team of researchers at the NIOSH used CFD, trace gas, and wire frame network model to determine airflow patterns around the longwall panels, airflow quantity and velocity in the tailgate bleeder system, and airflow pathways around the gob. The researchers concluded that the tracer gas can be used to determine airflow paths and retentions times in inaccessible areas of the gob. They further concluded that CFD can be used to explain various recorded peaks during tracer gas measurements [13].

Another team of researchers at the NIOSH conducted CFD modelling to optimize gas sampling locations for early detection of spontaneous heating by utilising a tube bundle system in a longwall gob area. Their research results showed that under bleeder ventilation system, optimum sampling locations are at the tailgate side and close to the back end, whereas for bleederless ventilation condition, optimum sampling locations depend on the location of coal source [14].

A CFD study of gas drainage for gob gas capture was conducted on Huang sha coal mine in Ci County, Hebei Province. Total gas emissions were 0.2 m^3/s. The length of gob modeled was 200 m. The results reported the presence of pressure sinks because of gob vent boreholes suction. The negative pressure region was sensitive to face ventilation. The presence of GVBs changed the characteristics of gob gas concentration by exhausting the methane out of the gob. The researchers also concluded that, to improve the efficiency of gas drainage and increase the gas drainage concentration, the location of drainage boreholes is important [15].

Currently researchers are working to develop software-based computer models to evaluate and analyse explosion risk in underground mine atmospheres. A team of researchers developed a gas explosion consultation software to evaluate the explosibility of a gas sample from underground atmosphere, determine degree of risk for not-explosive atmosphere, and for analysing other allied parameters. They tested the developed model and assessed explosion risk under various conditions using the developed software [16].

2. Permeability and porosity of the gob and strata

2.1. Gob parameters

The authors at Colorado School of Mines (CSM) developed geomechanical models in FLAC^{3D}, following the approach originally established by Esterhuizen and Karacan [9]. The geomechanical models were created using actual stratigraphic and rock mechanics data provided by cooperating mines. The models were then calibrated with real-time subsidence data along with longwall shield loading data. The gob porosity was determined as the difference between initial porosity of the gob and volumetric strain of the gob material as predicted by the model. The permeability was calculated from the porosity model using the Carman-Kozeny relationship for flow through porous media, as shown below (Eq. (1)).

$$k_{\text{gob}} = (k_{\text{initial}}/0.241)\left(n^3/(1-n)^2\right) \tag{1}$$

where k_{gob} is the permeability of the gob in mD; k_{initial} the initial permeability in mD; and n the porosity. Details about this geomechanical model can be found in a paper by Marts et al. [17]. The gob permeability ranges from 2.0×10^{-7} to 5.1×10^{-6} m^2 and the porosity ranges from 14% to 40%.

2.2. Strata and fractured zone

GVBs design, its performance, and placement depend on the distribution of permeability [6] in the fractured zone above the caved section where GVBs ended. In the past research, fractured zone permeability has been simplified using uniform values, which is not the actual case.

The permeability of coal-measure rocks highly depends on existing stresses and its post mining re-distribution [18]. In-situ permeabilities rely on the rock type in stratigraphy, however, they get modified by changing stresses. Durucan [19] presented the following relationship in empirical equation (Eq. (2)).

$$k = a\exp(-b\sigma) \tag{2}$$

where k is the permeability of the gob in mD; a and b the constants; and σ the applied stress.

Researchers at the University of Nottingham [20] conducted laboratory tests to develop the relationship between stress and permeability. The vertical and horizontal permeabilities of different layers of rocks in fractured zones were determined using developed stress-permeability relationships. Initial permeabilities of various rocks were based on published sources [9,17,18,20,21]. The equations used for calculating horizontal and vertical permeabilities are given below (Eqs. (3) and (4)).

$$k_{\text{h}} = k_{\text{ho}}\exp(-0.25(\sigma_{\text{yy}} - \sigma_{\text{yyo}})) \tag{3}$$

$$k_{\text{v}} = k_{\text{vo}}\exp(-0.25(\sigma_{\text{xx}} - \sigma_{\text{xxo}})) \tag{4}$$

where k_{h} and k_{v} are the modified horizontal and vertical permeability after mining induced stress, respectively; k_{ho} and k_{vo} the initial horizontal and vertical permeability, respectively; σ_{xx} and σ_{yy} the horizontal and vertical stress, respectively; and σ_{xxo} and σ_{yyo} the initial horizontal and vertical stress, respectively.

The Carman-Kozeny equation was used to calculate the porosity as shown below (Eq. (5)).

$$k \sim d^2\phi^3 \tag{5}$$

where ϕ is the porosity; and d = 0.25 m the grain size.

For the mine under consideration, the fractured zone is divided into five layers based on mining induced stress gradient and type of rock, as shown in Fig. 2. The permeabilities of the strata layers are given in Table 1.

One of the major uncertainties in longwall CFD modeling is the permeability input. A sensitivity analysis was conducted to examine changes in solution by altering the permeability in the gob and fractured zone. The permeabilities in the gob and fractured zone were varied by 10% and 20%, respectively, and the resulting changes in EGZ volume and GVB flow were documented and analyzed. A 20% decrease in permeability in the model results in 23% decrease in the EGZ volume. A 20% increase in the model permeability results in 36% increase in the EGZ volume. The 20% decrease in permeability also resulted in 16% less flow through the GVB, while a 20% increase in permeability resulted in 24% increase in the GVB flow.

The strata layer #1 sits immediately above the caved zone, as shown in Fig. 2. The permeability data for each strata layer was used in the CFD model in the form of a user defined function (UDF).

3. Model and ventilation layout

The CFD model (Fig. 3) was formed using air quality and ventilation related data collected from a coal mine situated in the western U.S. Data collection consisted of collecting mine geometric dimensions, caving characteristics of overburden, layouts of mine, lithology, operating ventilation conditions, and concentrations of gas. The width of CFD model panel is 314 m (1030 ft) and its height is 40 m (131 ft). The initial 13 m (42 ft) height is modeled as gob and remaining 27 m is modeled as fractured zone. At the top of the fractured zone there is a 2-m (6-ft) rider coal seam, which has been modeled as the methane inlet. The fractured zone has been divided into layers on the basis of rock type so that changes of permeability in the vertical direction can be accounted. The effect of mining induced stresses and fracturing is negligible above the rider coal seam. A massive, low permeability layer of shale is overlying the rider coal seam. This shale is not included in the model as its permeability is not expected to change significantly due to subsidence. The GVBs extend into the fractured zone and terminate above the caved zone. The length of the model is 457 m (1500 ft).

Input design parameters used in CFD modeling are based on field measurements and theoretical understanding. The base diameter of GVBs used in this study was 30 cm (12 in). The air quantity flowing through the longwall face was 33 m^3/s (70000 cfm), whereas the wellhead vacuum pressure GVB was considered to be 30 kPa (4 psi). Inlet quantity of methane was determined by mine measurements of methane ejected by the ventilation system and GVBs. The liberation rate of methane for 457 m (1500 ft) long panel was 0.47 m^3/s (1000 cfm). This is used as the base case in CFD modeling. Detailed information about CFD meshing, model setup, independence of grid, turbulence, convergence and solution are discussed in a previous publication by Gilmore et al. [22].

The CFD model was formed considering a "U" shaped ventilation design for a progressively sealed longwall panel, as shown in Fig. 4. The Unites States regulations normally require a bleeder sys-

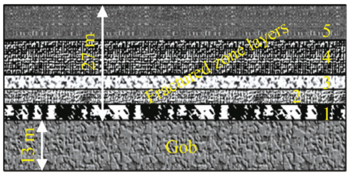


Fig. 2. Vertical cross section of gob and strata layers.

Table 1
Permeabilities of strata layers for the studied mine.

Strata layer	Thickness (m)	k_h (m^2)		k_v (m^2)	
		Min	Max	Min	Max
#1	3.0	1.1E−12	1.4E−12	1.3E−12	1.6E−12
#2	3.0	5.7E−13	6.8E−13	6.7E−13	7.8E−13
#3	3.0	3.8E−13	4.5E−13	4.4E−13	5.2E−13
#4	8.8	2.8E−13	3.4E−13	3.3E−13	3.9E−13
#5	8.8	1.8E−13	2.1E−13	2.1E−13	2.5E−13

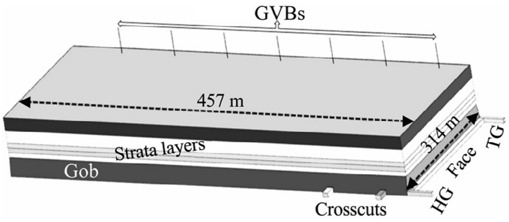


Fig. 3. Global CFD model geometry. Note that HG and TG are the headgate and tailgate, respectively.

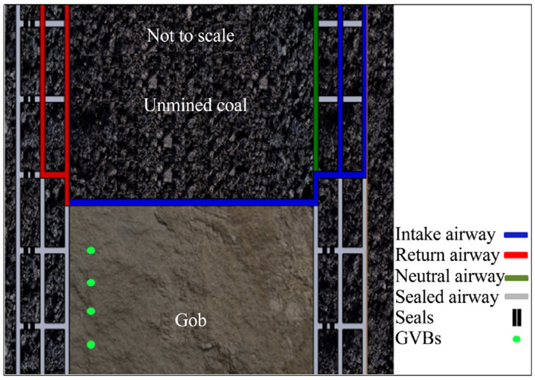


Fig. 4. Progressively sealed U-type ventilation.

tem [23]. Exceptions may be granted if the coal has a documented spontaneous combustion tendency. Many coals seams in western U.S. are prone to spontaneous combustion. Thus, various mines in this region control ingress of oxygen into the gob area by adopting progressive sealing (sometimes also referred to as bleeder-less panels). This is attained by progressively sealing the headgate side crosscuts inby the face as the panel advances. Thereby, the intake air travels across the longwall face after entering through the headgate and ultimately exits out through the tailgate.

4. Explosion hazard characterization

The explosive potential for air and methane gas mixtures is presented by a colored scheme based on Coward's triangle [24] in Fig. 5. Four distinguished zones are evident in Fig. 5. These zones include (1) an explosive zone (red zone), (2) an inert zone that is fuel-rich and this may become explosive with addition of oxygen or fresh air (yellow zone), (3) a completely inert zone that does not pose any chance to become explosive (green zone), and (4) a near fresh air zone (blue zone). A fifth zone (orange zone) was identified to represent such mine atmospheres that lie very close to explosive zone (red zone). Worrall et al. [24] correlated methane-air mixtures in CFD output plots with these colors by developing a UDF algorithm in FLUENT. The visualization of the EGZs in a plane at approximately middle of coal seam height (1.5 m) is shown by the contour plots in Fig. 5. The risk of spontaneous combustion is qualitatively assessed by evaluating oxygen concentration and ingress distance inby the longwall face. Spontaneous combustion of coal may be sustained by oxygen contents as low as 6% [25]. Brune and Saki [26] used mine measurements and CFD to demonstrate that EGZs form along the fringe areas (between the methane-rich atmospheres and the fresh ventilated areas along the working face) pose fire and explosion hazards to the mine workers.

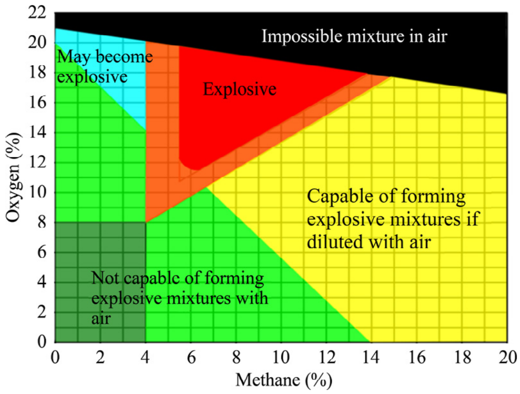


Fig. 5. Modified Coward's triangle [18] after Coward and Jones [28].

Researchers conducted a parametric study and discussed the effect of varying face air quantity on the formation of EGZs in the gob and concentration of methane in the tailgate. They found that increased longwall face air quantities may increase explosion hazard as they increase EGZ volumes in the gob and methane in the tailgate return [27].

5. GVB location optimization

The effectiveness of gob degasification for reducing methane concentrations in the work zones depends upon the location of GVBs on the longwall panel [29]. Diamond [6] demonstrated this in experimental field studies. In current study, GVB location is optimized to attain maximum methane reduction while minimizing the risks of losing GVB due to shear and gob compaction. Researchers varied distances of GVBs from the gate-roads and from the face and analyzed their effects. The base diameter of GVBs used in this study was 30 cm (12 in). The GVBs operated independently from each other. The total width of the modeled fractured zone is 304 m (1000 ft). The results of the location studies, as shown in Fig. 6, demonstrate that flow of GVB is maximum at 18 m (60 ft) away from the tailgate and 30–60 m (100–200 ft) inby the face. GVBs that operate closer to the face pose a risk of snatching fresh air from the face into the gob, thereby facilitating spontaneous combustion.

A series of studies was conducted to analyze the optimum location of GVB with respect to EGZ volume and for reducing methane

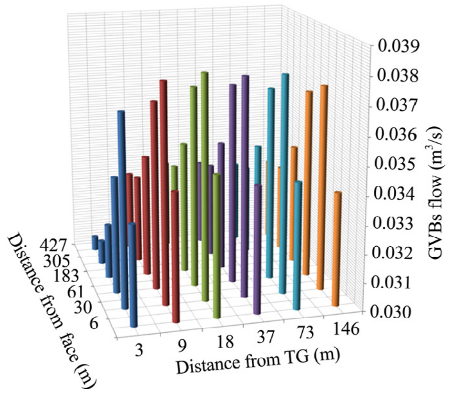


Fig. 6. GVBs flow with respect to the location.

concentration in the tailgate. Fig. 7 shows relative EGZ volume as a function of GVB location. EGZ volume is found to be minimum at 18 m (60 ft) away from the tailgate. GVBs that lie near the center of the panel cause more fresh air ingress from the headgate side, forming bigger EGZs. Fig. 7 shows that GVBs far inby the face cause the formation of larger EGZs because of pulling fresh air deeper inside the gob.

Fig. 8 shows the contour plots of EGZs for two GVB locations. The image on the left side shows the EGZ for a GVB operating at 18 m (60 ft) from the tailgate. The image on the right is for a GVB operating in the center of panel at 146 m (480 ft) from tailgate and it creates a slightly larger volume of EGZ.

Fig. 9 shows a comparison of GVB effect to reduce the concentrations of methane in the tailgate return airway. GVBs at 18 m (60 ft) are also most efficient in reducing methane concentrations in the return airway. Karacan et al. [10] also reported that the GVB setting depth impacts the quality and quantity of methane exhaust from GVBs. The presence of shear bands or horizontal shear zones in the gob can damage borehole's casing and it can partially or completely block the GVBs. Lowndes et al. [18] predicted that horizontal shear planes may develop within the immediate roof of the mined coal seam. Shearing of GVBs can be avoided by setting the depth of GVBs above the caved zone. The caved zone and its surroundings exhibit higher permeabilities as compared to fractured zone. Therefore, if a GVB is set within the caved zone it will draw more air through the gob and the concentration of methane in the GVB exhaust will drop. It is recommended to terminate the GVBs above the caved zone to avoid the sharing of GVBs. It also helps to reduce air ingress into the gob and hence reduces the risk of spontaneous combustion. Lower air ingress into gob may help to reduce the size of EGZs in the gob and hence the explosion hazard.

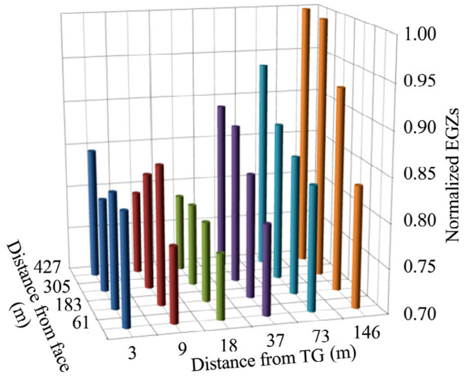


Fig. 7. EGZs comparison with respect to the GVBs location.

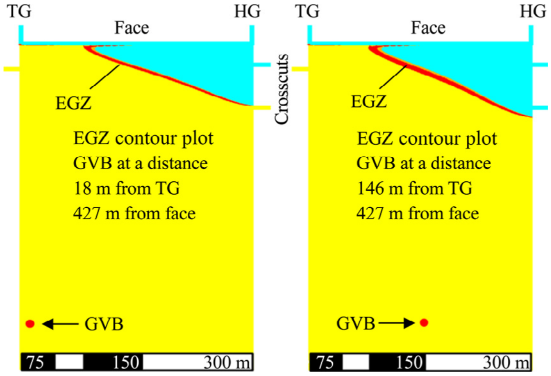


Fig. 8. EGZs contour plot comparison.

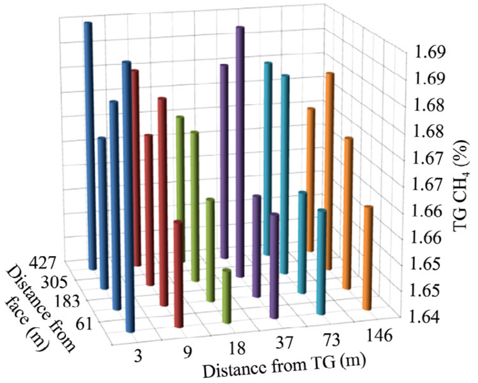
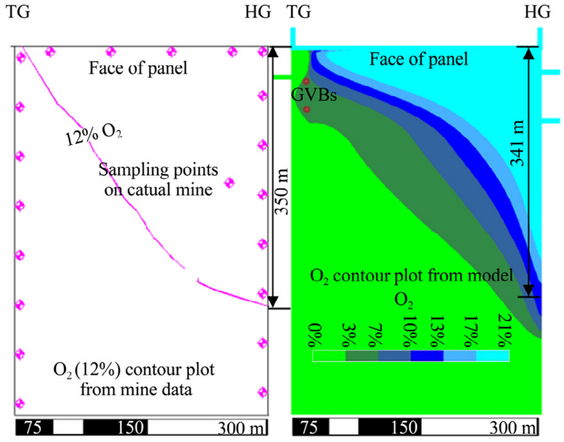


Fig. 9. Tailgate methane comparison with respect to GVBs location.

6. Model validation

The authors validated the models' predictions with the gas measurements conducted at the mine site by the mine. The co-operating mine used a tube bundle gas analyzer system that allowed the measurements along the fringe of the gob. The mine also provided the gases measurements data collected through sealed sampling tubes and from manual readings at the mine face. Additionally, discussions with mine personnel helped to validate the results. Oxygen ingress in the model was compared with that of an actual mine at actual operating conditions, as shown in Fig. 10. Fig. 10a shows the 12% oxygen contour plot from actual



(a) The 12% oxygen contour from the actual mine

(b) The oxygen contour from the model

Fig. 10. Validation of CFD model predictions of oxygen concentrations profiles with oxygen measurements from a mine.

mine data while Fig. 10b shows the oxygen contour plots from the model. The model predictions agree with oxygen measurements conducted at the cooperating mine. The general results of the CFD models agreed with the operator's 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 the mine. The operator experienced that the methane enters the face primarily at the tailgate corner as shown by the models in Fig. 8. The operator also reported low oxygen concentration behind the shields inby the tailgate corner, which matched the models results shown in Fig. 10b. Further details on model validation can be found in Saki's dissertation [29].

7. Assumptions, approximations, and limitations

Several assumptions were made regarding the complex mine geometry and during the CFD modeling process. The shield leakage into gob was represented by gaps in the model face. There was no leakage through the seals. The three headgate and tailgate development entries were modeled as a single entry. The only methane source was at the top rider coal seam. The methane gas that flows into the models was uniformly distributed over the top of the fractured zone. The methane source was continuous and did not deplete over time. The barometric pressure was considered constant over the period of panel mining.

The modeling results are sensitive to the assumptions made like permeability of gob/strata and amount of methane in the model. The assumptions are made due to the limited availability of data inside the gob. Sensitivity studies were run on assumptions parameters. Increased methane in the model decreases the size and volume of EGZs, while increases the methane concentration in the returns and GVBs exhaust. The modeling results are quite sensitive to the change in permeability of gob and fractured zone. Increase in permeability increases the methane coming into the model and hence decreases the EGZs, while decrease in permeability reduces the amount of methane in the model and hence increases the size of EGZs. Lower the permeability, higher the flow through GVBs and vice versa.

8. Summary and conclusions

The following conclusions were drawn from this research.

(1) The optimal GVB location with respect to the GVBs flow, explosive gas zone formation, and reducing concentration of methane in work zones is 18 m (60 ft) from the tailgate for the studied mine.
(2) Near face GVBs exhibit low concentrations of methane as compared to far face GVBs. This is because near face GVBs pull more ventilation air.
(3) Deep air ingress into the gob area is caused by GVBs that lie at a far distance from the longwall face.
(4) Larger EGZs are formed by the GVBs that lie at a far distance from the longwall face. These GVBs are also less efficient in decreasing concentrations of methane in work zones.
(5) Methane concentration in GVBs is determined by the setting depth of GVBs. Thus, the setting depth is a significant factor in deciding GBVs performance.

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