RESERVOIR ENGINEERING CONSIDERATIONS FOR COAL SEAM DEGASIFICATION AND METHANE CONTROL IN UNDERGROUND COAL MINES

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ABSTRACT

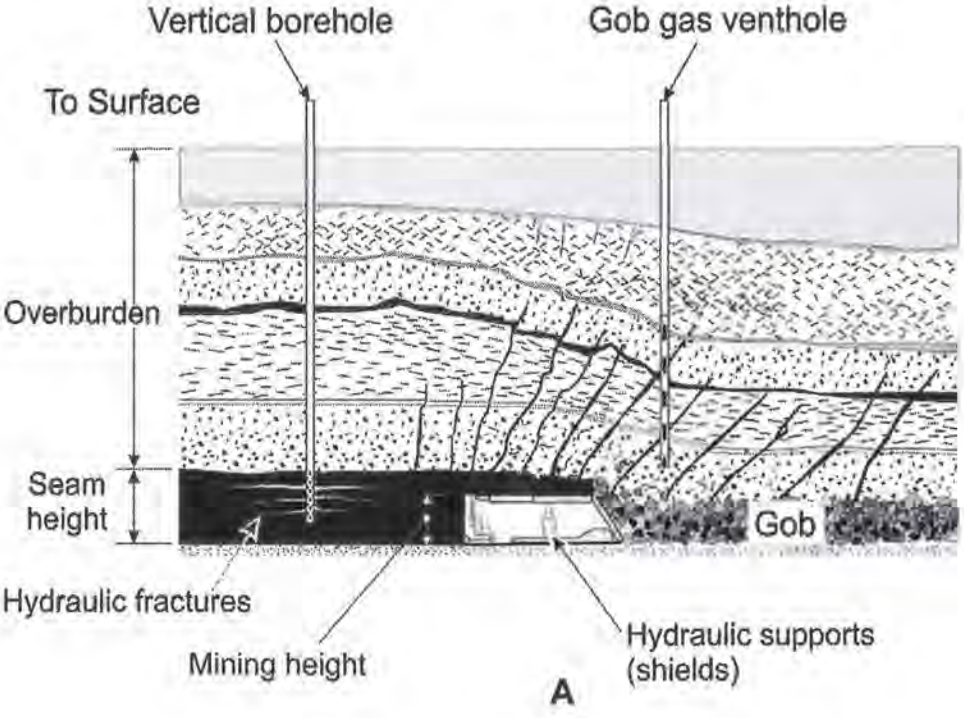
Degasification and methane control in underground coal mining is an important area augmenting conventional ventilation in order to prevent possible fires and explosions due to excessive methane emissions. Coal bed reservoir engineering has been applied for many years to coalbed methane production. In recent years, modeling the flow and draining methane, not only from coal bed itself but also from the overlying strata, have been recognized as important areas of expertise for supplementing underground ventilation. This paper demonstrates the applications of coal bed reservoir engineering and modeling techniques for optimizing and controlling methane emissions in longwall and continuous miner sections. Practical applications and some considerations are presented for reservoir modeling, borehole performances, and face emission predictions for various coal bed and borehole configurations. A section on field reservoir studies and wellbore log analyses for methane control are also presented as a complementary way of controlling methane and optimizing ventilation.

1. INTRODUCTION

High methane liberation rates experienced during mining can result from reservoir properties of the coal bed and mining conditions. For instance, in the case of development mining, the emissions can result from the intrinsic properties of the coalbed reservoir or from properties of the mining operation such as mining rate, mining height, and entry length, to name a few. In longwall mining, the properties of the mined coal seam, as well as the properties of overlying strata, can be important since this method can create large-scale disturbances in the overlying strata. These disturbances manifest themselves as cavings of immediate roof, fracturings and separations of bedding planes and bending zones, each of which may have different properties depending on the strata characteristics and the height of the mined seam. In longwall mines, the "gob" may be the greatest source of methane emissions. During mining, high methane emissions and subsequent increases in methane levels must be diluted and removed from the active workings by the ventilation airflow.

Unfortunately, the emissions may not be controllable by ventilation alone or by changes in mining parameters. Generally, it is economically feasible to handle specific emissions (total gas emission per unit amount of coal mined) up to 1000 ft^3/ton with a well-designed ventilation system. At higher specific emission rates, however, it is difficult to stay within statutory methane limits using ventilation alone (Thakur, 2006). Thus, supplementary methane control measures are needed including degasification of the coalbed prior to mining, use of vertical or horizontal boreholes, or use of gob gas ventholes. Figure 1 shows a schematic representation of the mining environment and the different types of supplementary controls commonly used in U.S.

The recognition of methane in coal beds as a valuable resource has led to the development of different numerical approaches for modeling flow mechanisms of gas and water in coal seams (King and Ertekin, 1991). The finite-difference-based models described by King and Ertekin (1991) have continued to be the most widely accepted and applied techniques for simulating the complex storage and transport processes in coal beds. These models have also been used to model methane emissions and borehole productions with special site-specific considerations including gas emission potential of the coal seam, its reservoir characteristics and geologic factors that may affect the flow of gas during degasification and mining. This paper is an overview of possible reservoir engineering considerations, including numerical modeling and field measurements, for controlling methane in coal seams.



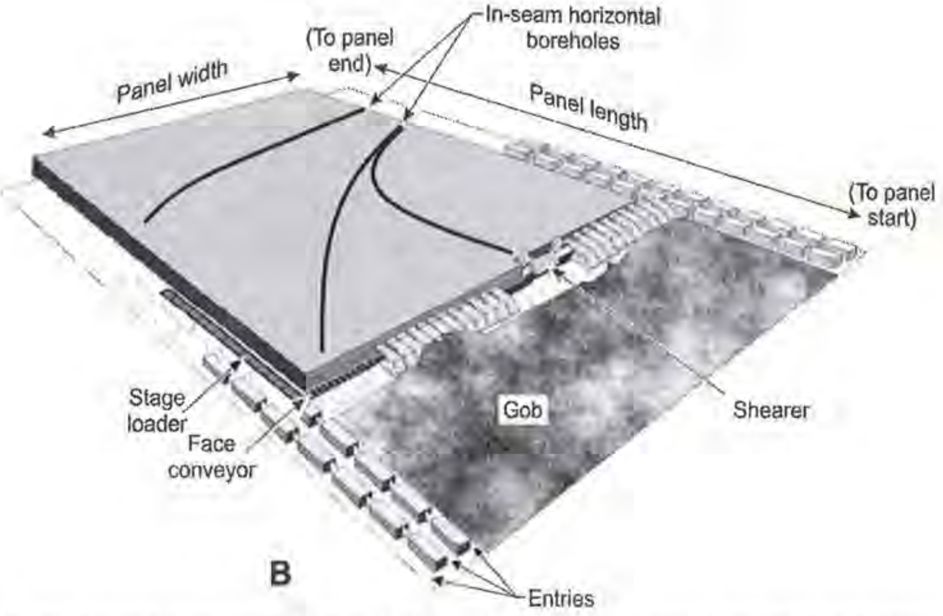


Figure 1: Schematic representation of the mining environment and the different types of degasification boreholes commonly used in U.S. (Karacan, 2009)

2. CHANGES IN RESERVOIR PROPERTIES OF OVERBURDEN DURING LONGWALL MINING AND SLUG TEST APPLICATIONS

Methane inflow from overburden strata during longwall mining is affected by the magnitude of fracturing and the time that the fractures stay open as the panel is extracted. The reservoir characteristics and their changes during mining can affect production potential of the gob gas ventholes that are commonly used to control the methane emissions from the fractured zone. These holes are typically drilled from the surface to a depth that places them above the caved zone. Thus, the ability to predict changes in formation characteristics based on various factors at a given location increases the understanding of gob gas venthole production and can optimize the placement of these holes to improve their productivity.

For the characterization of both the fracturing of underground strata and the resultant changes in hydraulic conductivity in the gob gas ventholes (GGV's) during longwall mining, seven boreholes were instrumented with submersible pressure transducers equipped with self-contained data loggers at a mine site in SW Pennsylvania. The change in water head was monitored during longwall mining. The data were used to calculate hydraulic conductivities and were plotted as a function of different parameters (Figure 2).

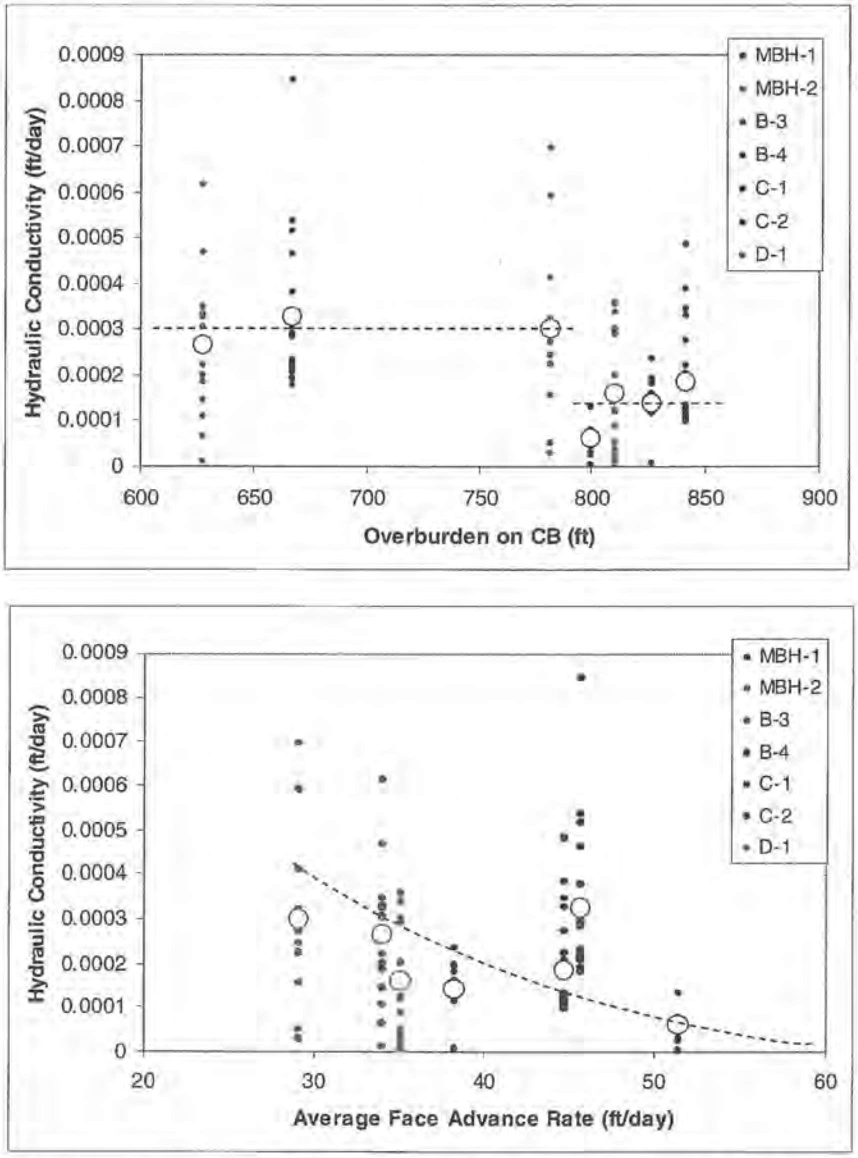


Figure 2: Hydraulic conductivity changes in the overburden plotted as a function depth and face advance rate (Karacan and Goodman, 2009). The circles are the averages of measurements at each borehole

Based on the slug tests and other data used in Karacan and Goodman (2009), it was concluded that the locations of the boreholes impacted their fracturing time and the resultant hydraulic conductivities. Results showed that greater overburden depths led to lower hydraulic conductivities and potentially less productive boreholes as opposed to shallower GGV's (Figure 2). In addition to overburden depth, mining advance rate was found to be effective also on the hydraulic conductivities. It was shown that higher face advance rates at the study mine site resulted in generally lower hydraulic conductivity in the fractures. This may be due to the rapid change of tensile stresses to compressive stresses that reduces fracture conductivity.

In order to determine where the fractures may be occurring, a similar approach that was used by Palchik (2005) was adapted for the rock layers in the overburden of the

Pittsburgh coal. Observations on the presence and absence of horizontal fractures at different rock-layer interfaces of the overburden showed that the probability of layer separations increased with increasing compressive strength difference of neighboring rock layers as well as decreasing distance of the layer from the mined coal bed. Palchik (2003) noted that separations at the interfaces and formation of fractures may be restrained by thick and strong rock layers, called "bridge layers", in the overburden. The "bridge layer" in the study area was the thick limestone close to the top of the overburden. Also, the probability of bedding plane separations along the rock layer interfaces decreases with increasing height above the coal seam (H), with increasing thickness of the bridge layer, and with the increasing ratio of formation thickness (h) to the coal seam thickness (m). Therefore, in the study boreholes, it is more probable that such deformations will occur within an interval between 40 ft-145 ft from the top of coal bed and up to h/m of 4 (Figure 3). This interval contains thinner limestones, sandstones and weaker strata, such as coal beds an shale, and will indicate where the slotted section of gob gas ventholes should be located (Karacan and Goodman, 2009a).

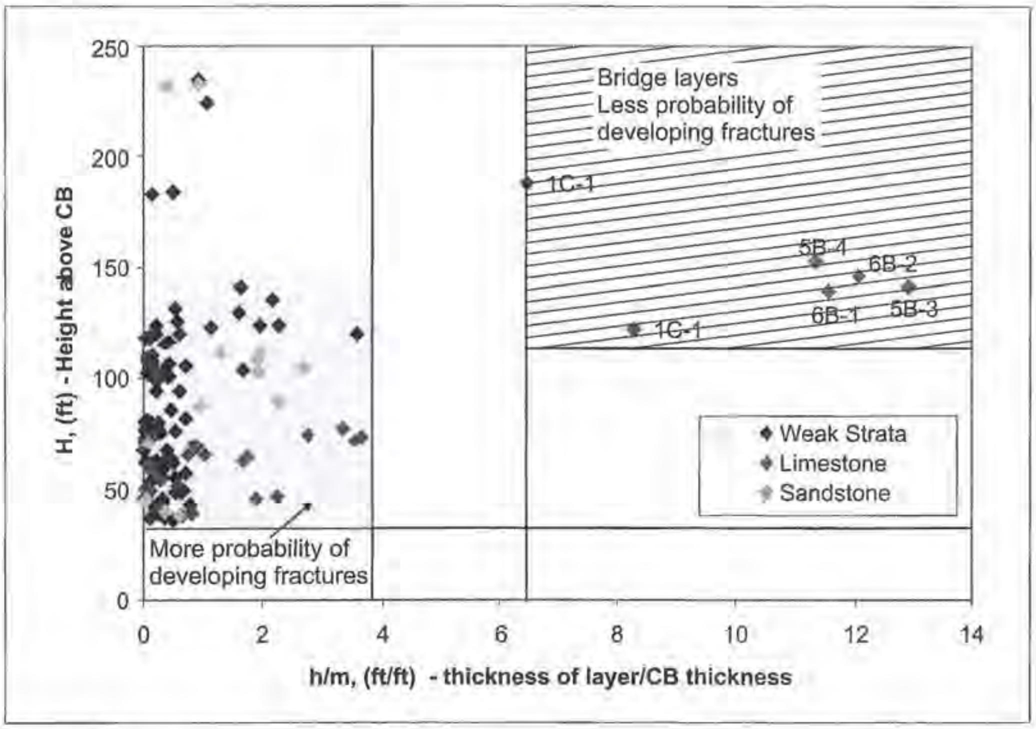
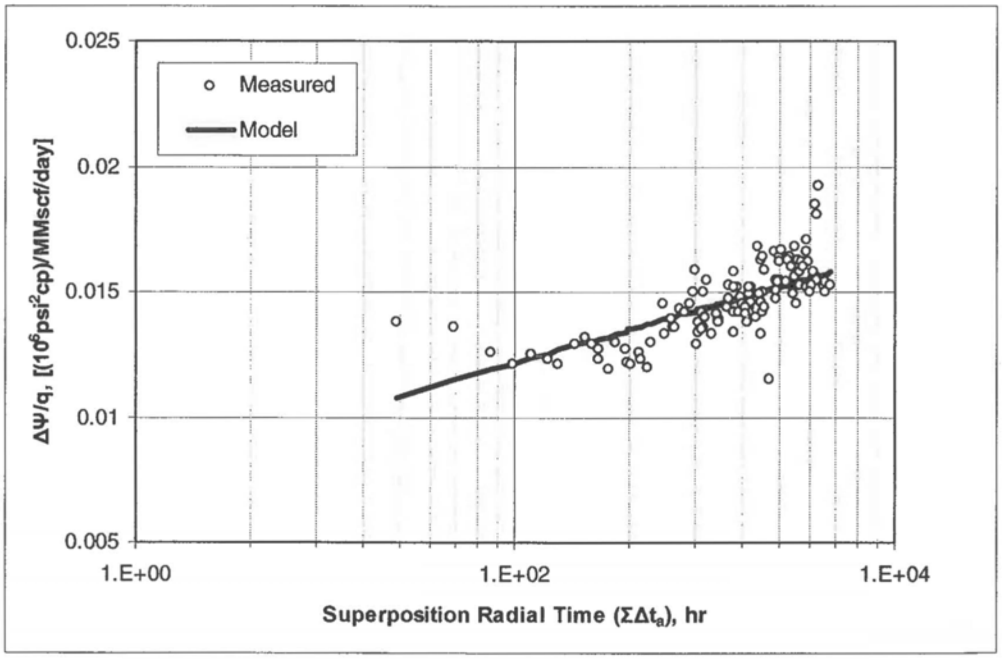


Figure 3: A plot of the ratio of thickness of each layer to extracted coalbed thickness and their heights relative to the top of the extracted coalbed. This graph also shows the strata identifications as sandstone, limestone and weak strata (coal, shales of all kind and clay stones)

3. WELL-TEST ANALYSES METHODS FOR APPRAISAL OF RESERVOIR PROPERTIES

Improvements in gob gas venthole gas drainage evaluation and prediction capabilities for site-specific mining conditions and circumstances can address longwall gas emission issues, resulting in ventholes designed for optimum production and mine safety and also for improved gas capture. It is difficult to predict production performance of gob gas ventholes due to the involvement of multiple influential factors, the complex properties of the gob, and the lack of knowledge on interactions of the GGV's with the gob reservoir.

Routine production tests are performed in the oil and gas industry for long-producing wells in order to identify their productivity changes and to better manage the reservoir. Owing to the importance of the measurement and analysis methods, various researchers developed techniques to test conventional oil and gas wells. (Kuchuk and Onur, 2003). In this study, multi-rate drawdown gas well test analysis techniques were applied to understand the behavior of the gob gas ventholes and the reservoir properties of the gob. In order to achieve this objective, the production rate-wellhead pressure behavior of six gob gas ventholes drilled over three different panels was analyzed for parameters such as skin, permeability, radius of investigation, flow efficiency and damage ratio. In these analyses, the venthole production periods during panel mining (DM) and after mining (AM) were analyzed separately using infinite flow and pseudo-steady state (PSS) flow models in a composite reservoir, respectively; since the reservoir capacity, behavior and gas production potentially change between these two phases (Karacan, 2009b). Figure 4 shows plots of real gas flow potential versus superposition time for a gob gas venthole. Various reservoir properties were calculated from the slopes of these plots (Table 1).



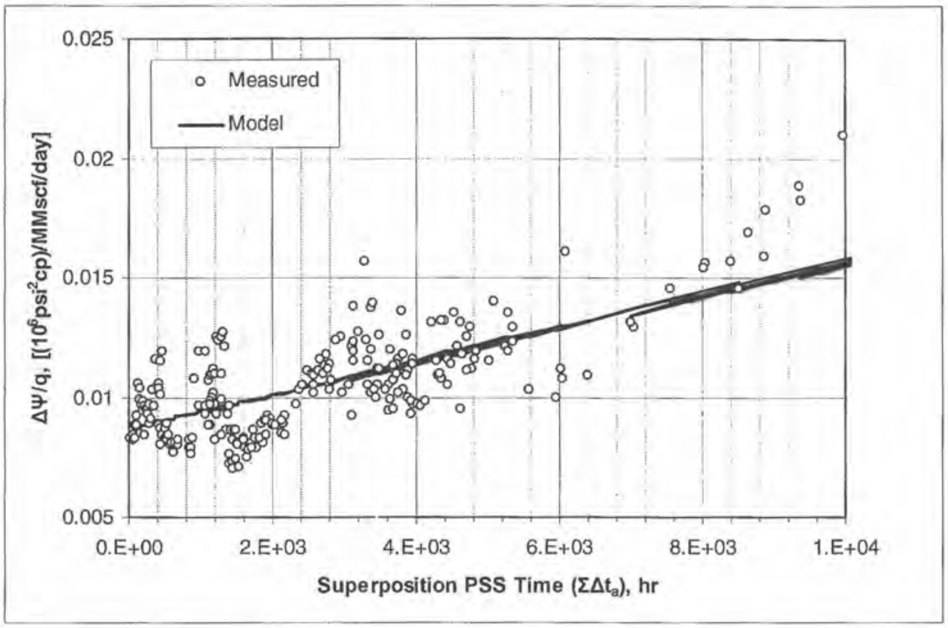


Figure 4: Superposition time versus real-gas flow potential for a gob gas venthole's DM and AM production phases, using infinite-acting and pseudo-steady state boundary conditions, respectively

Table 1. Reservoir properties calculated for gob using multi-rate drawdown Techniques ($r_{e1,2}$: radii of investigation of the tested borehole, $k_{1,2}$: gob permeability, FE: flow efficiency, DR: damage ratio)

	DM	AM
r_{e1} (ft)	1198.9	579.8
k_{re1} (md)	1173.0	1937.1
r_{e2} (ft)	inf.	9179.2
k_{re2} (md)	1974.4	10788.2
Total skin (s')	-5.5	-3.6
Mechanical skin	-4.5	-2.6
Final rate (MMscf/day)	0.406	0.073
Cum. prod. (MMscf)	59.143	31.046
Final flow pressure (psia)	11.9	12.4
Ave. error (%)	1.08	0.79
FE	2.2	1.8
DR	0.5	0.5

Table 1 shows that the near-borehole radius of investigation of the borehole decreased after completion of the panel as a result of boundary effect. Permeability, on the other hand, showed an increasing value at the AM phase, compared to the DM phase, within the boundaries of the gas reservoir. Total skin and FE values decreased due to reduced gas production and near-borehole effects. The results specific to this study and the mine site showed that although the gob reservoir and venthole data calculated using well testing methods generally corroborated the measured productivity of the ventholes, there were other factors that should have been considered in evaluations (Karacan, 2009). For instance, reservoir heterogeneities during caving and formation of the gob were very complex and were highly dependent on the local strata. In such an environment, the locations of the ventholes were of critical importance. This study showed that ventholes located close to the entries, particularly tailgate entries, produced better. It was shown that conventional well test techniques could be a valuable tool for reconciling gob gas reservoirs and gob venthole performances since there was no other more effective alternative.

The same or similar well-test analysis techniques can also be used for vertical and horizontal degasification boreholes to determine the relationships between their production efficiencies and the decrease of in-mine emissions. The analyses results can be used to determine coal seam reservoir parameters and to design degasification borehole locations accordingly.

4. METHODS FOR FURTHER FORECASTING GGV PERFORMANCES

Despite the improvements in analytical and numerical modeling approaches, experience suggests that it is still difficult to accurately predict methane production for gob gas ventholes and that these predictions may be underestimated relative to actual gob gas venthole production by at least a factor of two or more. The key factor to this underestimation is the difficulty in incorporating in any predictive approach the many factors that affect venthole performance (Zuber, 1998). In almost all cases, these factors are related non-linearly to each other and to the production performances. Thus, production predictions may be more successful if these non-linearities can be understood and unconventional modeling techniques, such as artificial neural networks (ANN), can be used to handle these non-linearities.

In order to predict gob gas venthole production rates and methane concentrations in the face of many complicating factors such as venthole location, mining parameters, borehole location with respect to panel and surface terrain, and exhauster pressure, the production data that were obtained from 10 gob gas ventholes drilled over three adjacent panels mined in the Pittsburgh coal bed in the Southwestern Pennsylvania section of the Northern Appalachian basin were analyzed (Karacan, 2009c). The production data were obtained by monitoring these ventholes for flow rate and methane concentration during and after panel extraction. The ANN model was built using a multilayer perceptron (MLP) approach and was trained (calibrated) and tested using the database to achieve minimum mean square error and high correlations between measurements and predictions. After a reasonable prediction with ANN was obtained, sensitivity analyses were run about the means of the input variables to better understand the effects of each of these inputs on predicted outputs.

Table 2: Sensitivity (in standard deviations) of gas flow rate and percent methane to individual input parameters used in the ANN model and the total sensitivity (third column) when both performance parameters are combined. Shaded cells are the total sensitivity above the average sensitivity value (33.8) calculated using all inputs

Input Variable	Gas Rate	Percent Methane	Total (Std. Dev.)
Panel Completed (Yes)	13.1	8.1	21.2
Panel Completed (No)	28.2	3.6	31.9
Is Face Advancing? (No)	24.3	10.3	34.7
Is Face Advancing? (Yes)	18.7	0.3	19.0
% of Panel Mined	45.2	3.1	48.3
Linear Advance Rate	7.5	1.4	8.9
Surface Elevation	34.4	6.6	41.0
Overburden	16.1	4.2	20.3
Casing Diameter	81.2	4.4	85.6
Casing Distance to Coalbed	7.7	2.2	10.0
Distance to Tailgate	67.7	1.7	69.5
Distance from Panel Start	52.3	12.2	64.5
Panel Length	37.7	4.3	41.9
Panel Width	5.1	1.4	6.5
Barometric Pressure	14.0	0.6	14.6
Average Vacuum at Wellhead	22.1	1.9	24.0

Sensitivity analyses about the means of the input variables were conducted using the ANN model to identify which input variables had more influence on the performances of gob gas ventholes (Karacan, 2009c). The results of these analyses showed that for total gas flow rate (a) percentage of the panel that has been mined, (b) surface elevation of the ventholes, (c) casing diameter, (d) distance to tailgate, (e) distance of the venthole to the start of panel, and panel length were most influential. However, for GGV methane percentage (a) distance of the venthole to the start of the panel, (b) whether or not panel is completed, (c) whether or not face is advancing were most important. When considering the overall performance of gob gas ventholes for both flow and methane percentage, (a) whether or not face is advancing, (b) percentage of the panel that has been mined, (c) surface elevation of the venthole (above sea level), (d) casing diameter, (e) distance of the venthole to the tailgate, (f) distance of venthole to panel start, and (g) panel length were important variables.

5. MODELING OF BOREHOLES IN COAL BEDS WITH FAULTS

Impermeable geologic faults in the coalbed can cause intermittent production problems or can cause unexpected amounts of water or gas to issue from degasification boreholes. These faults also can impact methane emissions into the mine workings, especially if they hinder proper and effective degasification of the coalbed. They may also act as barriers for methane flow in the coalbed. Although this might seem beneficial for advancing mine workings, faulting may also cause gas pressure buildups and result in compartmentalization of the gassy regions from which large quantities of water and methane may rush into mine workings.

The effects of impermeable faults on coalbed degasification efficiency using vertical and horizontal boreholes were assessed using numerical reservoir simulation. Three different fault configurations were simulated: no throw, up throw, and down throw. To create throws, the fault block on the borehole drilling side was kept stationary, whereas the vertical positions of the grids in the other fault block were moved by +/- 3 ft up and down based on the throw direction. The geometry of the vertical borehole was not affected by these changes. However, in the case of the horizontal borehole, the borehole trajectory was adjusted after it penetrated the moving block, based on the throw amount and direction so that the borehole was always horizontal in both blocks. Figure 5 shows the grid models that represent these situations.

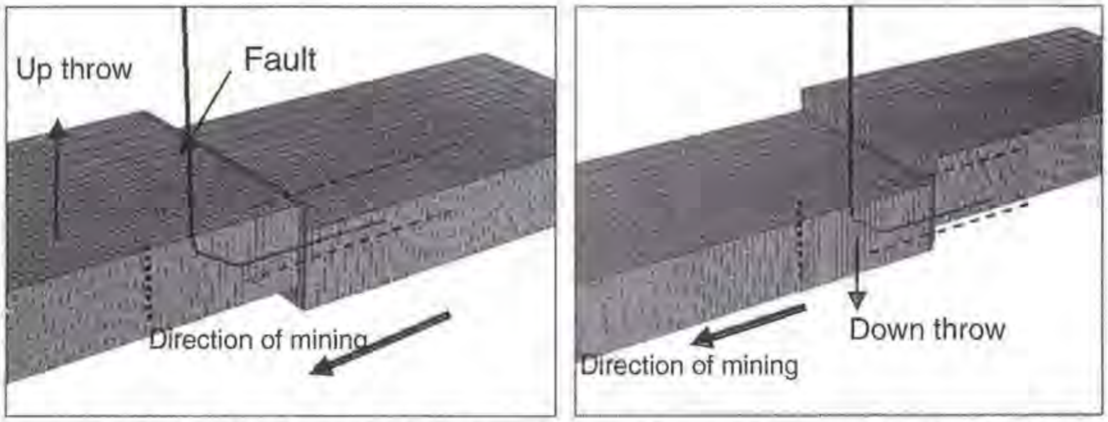


Figure 5: Coalbed models that show the modeling of impermeable faults with downward throw and upward throw. The figures also show the relative positions of horizontal and vertical boreholes in each case

The advance of a 1200-ft wide longwall panel whose start-up end was 1400 m (4500 ft) away from the borehole drill locations (Figure 5) was modeled. Mining progressed in the direction shown in Figure 5. Face advances were characterized by sequential "regions" with lengths of 225 ft within the grid model. These regions represented the coal blocks to be mined during the mining process. This "proxy" approach to the moving boundary problem (Karacan *et al.*, 2005; 2007a; 2007b) enabled the determination of "remaining adsorbed gas volume" in the coal matrix and the "free gas and water volumes" in the fractures (cleats). These volumes could be determined at any time after a certain operational period of the boreholes or they could be evaluated as a function of distance from either the start of the panel or from any of the modeled discontinuities. The gas and water quantities monitored and recorded by the simulator in each "region" were used to calculate potential emissions for a 30-ft/day average face advance rate in the presence of stratigraphic discontinuities or geologic anomalies in the coalbed (Karacan *et al.*, 2008).

The results given in Karacan *et al.* (2008) showed that for a coal bed degasified using a horizontal borehole, the maximum changes in methane emission and water inflow to the mine occurred around the fault location, particularly while the mining face passed through the fault with a down-throw. This might be due to the fact that the bulk of the reservoir volume on the right side of the fault line remained underneath the borehole trajectory. The methane at the top of the reservoir was produced effectively, while the remaining gas stayed in the coal bed and was released into the mine during mining operations. The next highest emission occurred when there was an up throw along the fault line. This might be because the borehole was positioned close to the bottom of the coal bed on the right-side reservoir block and possibly flooded by water entering the borehole by gravity drainage (Karacan *et al.*, 2008).

On the other hand, the effects of fault geometries on emissions after degasification with a vertical well showed that there would be a sharp decrease in methane emissions and water inflow after the mining face passed through the fault into the borehole block which was degassed effectively. Therefore, it is important to locate the fault and determine the presence and extent of any throw in order to plan more efficient borehole drilling and placement strategies.

6. SUMMARY AND CONCLUDING REMARKS

Degasification of coal seams and methane control in mines using vertical, horizontal and gob gas ventholes are very important for the safety and productivity of any underground coal mining operation. Despite the importance of degasification and methane control to supplement conventional ventilation for eliminating high methane levels, there are no standard methods or dedicated techniques to determine coal and gob properties or to optimize borehole locations. In this regard, it has been shown that reservoir engineering techniques are very suitable and promising. Coalbed methane reservoir modeling, estimation of fractures to better locate slotted casings, well test analyses techniques and intelligent computing methods can be used to determine coal and gob reservoir properties to optimize well locations. These techniques give a better understanding of wellbore productivities and help to determine the relations between various parameters and the efficiency of controlling methane in mines.

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