International Journal of Rock Mechanics & Mining Sciences 63 (2013) 148–158

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Technical Note

Use of reservoir simulation and in-mine ventilation measurements to estimate coal seam properties

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ARTICLE INFO

Article history:
Received 8 June 2012
Received in revised form
9 May 2013
Accepted 4 August 2013
Available online 13 September 2013

Keywords:
Reservoir simulation
Coalbed methane
Coal mine methane
Mine ventilation
Coal reservoir properties
Mine safety

1. Introduction

Methane is a safety concern in underground coal mines. In its explosive range of 5%–15% in air, methane can be easily ignited in the presence of an ignition source to create a violent methane explosion. Ventilation is the main control mechanism to keep methane levels below the explosive limit. However, effectiveness of a ventilation system is dependent on multiple factors such as geological conditions, mine design, and reservoir properties of the coal seam. Without good knowledge of these factors, methane emissions can still create a localized zone of high methane concentrations in areas of low air velocities and quantities, and can render the ventilation system ineffective. Among those factors controlling methane emissions, reservoir properties of the coal seam are particularly important, especially if the mined seam is the main source of methane, with the properties of the coal controlling methane storage and emission potential during mining operations.

If not diluted by ventilation air, methane in coal seams is not only a hazard to mining safety, but an important concern from an environmental point of view as a greenhouse gas. Capturing and utilizing methane from active mines will both improve mining safety and decrease greenhouse gas emissions, and will provide an additional energy source that otherwise will be lost. A similar concept is also true for sealed workings and abandoned mines, as methane accumulating in these areas can be detrimental for active mines operating nearby in the event of gas migration between the workings. Methane accumulations can also be used for energy production if captured. Methane capture and utilization technologies have been demonstrated and are being successfully used mainly in the US and in Australia, and in other countries around the world [1].

There are various geological and operational factors affecting a mine's methane emissions during coal extraction. Therefore, a relative term called "specific emissions" is used as a lumped parameter to designate the gassiness of a mine. Specific emissions are the amount of methane generated per unit amount of coal that is mined [2], and this quantity is generally used to determine the degasification and ventilation needs of a particular operation. It has been shown for Australian mines that the amount of mine emissions exceeded the gas content of coal by a factor of 4 [3]. This ratio is due to the fact that methane that leads to specific emissions of a mine may be generated from the mined coal itself, and also may originate from overlying and underlying strata if they are gassy. In addition, the quantity may change based on variations in operational parameters.

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1365-1609/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.ijrmms.2013.08.008

While gas content of a coal seam is one of the key data impacting in-place coalbed methane resource estimations, it is not the only parameter important to coalbed and coal mine methane assessments. Coalbed methane and coal mine methane production potentials are affected by coal reservoir properties, mining conditions, and coal productions. This is one reason why coal production is used as a major parameter in most empirical models of methane emissions, and why coal production should be reevaluated under ventilation constraints [4].

Degasification of methane from coal seams and from adjacent strata which is a common practice, especially for long wall mines operating in gassy coal seams. Degasification can be used for controlling methane emissions prior to and during mining by reducing emissions into the ventilation system. Reducing the gas content of coal seams either by using vertical boreholes drilled from the surface, using horizontal boreholes drilled from adjacent entries, or by drilling directional boreholes from the surface, are effective ways to control methane emissions [5–7]. Multi-lateral horizontal boreholes are drilled from a single drilling location in the head gate entry to reduce the gas content of the coal volume in the panel area before mining. Boreholes drilled from various locations in the main entries extend into multiple panel areas to drain the gas in a larger area before mining commences. Multiple wells can be connected for transportation of the gas within the mine. Numerous studies have demonstrated that under continuous and uniform coal seam conditions, the performance of the boreholes and their effectiveness at reducing emissions can be predicted by modeling techniques [8,9].

Regardless of whether methane emissions can be controlled by ventilation alone or by any pre-mining degasification method, fluid-flow and fluid-storage related properties of the coal seam have to be known. Coal reservoir properties of the mined seam are not only important for methane emissions into the ventilation system but also for the success of degasification operations. Effects of various mining and coal reservoir properties on potential emissions into entries during development mining of coal seams are discussed in [10,11] using dynamic reservoir simulation, where as the effects of water jetting on decreasing outbursts and improving entry development rate is discussed in [12].

If there are wells operating in the mining area for degasification purposes, then properties of mined coal seams can be determined or estimated using different techniques, including laboratory analyses [13,14], geophysical logs [15], and well testing methods [16]. History matching of pressure and production behavior of these wells using reservoir simulation can also estimate properties of the coal seam being degasified. Each of these methods has advantages and disadvantages. Although laboratory analyses can be informative, it is difficult to reproduce in-situ conditions in the laboratory. Therefore, not all data measured in the laboratory may be representative of in-situ conditions. Geophysical methods can be effective to measure some of the reservoir properties pertinent to porous rocks and coal seams. However, permeability should be inferred from other measurements. On the other hand, well testing techniques can produce data that are more representative of in-situ conditions, but these methods are complicated, expensive, and sometimes require lengthy times to gather and process the information. In addition, geophysical logging, well testing, and production/pressure history matching techniques all require wellbores that are either producing or that can be used in reservoir testing.

Coal mining areas may not necessarily have boreholes that are equipped for well testing and history matching purposes. Although not every mining area is expected to have degasification wells that make the history matching technique applicable, all coal mines must measure airflows and methane concentrations regularly at specific locations in the ventilation network. Thus in this study, an alternative approach is proposed to predict coal seam reservoir properties through integration of ventilation data measured in entries with numerical reservoir simulation. Because all coal mining operations must make ventilation measurements at specific locations, these types of data are always available. To our knowledge, this approach and the history matching of ventilation air data have not previously been tried and demonstrated in the literature for estimating coal seam reservoir properties.

2. Location of mine, properties of coal, and geology of the area

The Yeni Celtek mine is located in the Suluova basin, which contains thick and laterally extensive Lower Eocene coal seams, approximately 35 km northwest of Amasya and 90 km of Samsun (Fig. 1, inset image). The formations in the Suluova basin are folded and faulted with lateral and vertical displacements (Fig. 1). The structural properties of the basin reflect on the maturation properties of coal as well, in such a way that there is a transition from lignite to sub-bituminous rank depending on the location. This transitional character in coal rank combined with the structural characteristics of the basin may be one of the reasons that the study mine is experiencing intermittent and sometimes continuous gas emissions during mining.

The basement of the Suluova basin consists of Jurassic-Cretaceous gray limestones, which are thinly bedded and include claystones within the coal seams. The coal seam and the overlying bituminous shales, which contain abundant amorphous kerogens with characteristics of those formed in fresh water environments, are thought to be deposited in a lacustrine environment [17]. The stratigraphy of the basin also includes alterations of conglomerates and sandstones (Fig. 2).

The mine operating in the area produces coal using longwall operation from a seam that has ~30 million tons of reserves. Thickness of the mined coal seam ranges from 5 to 8 m. However, the quality of the coal changes within the seam and the coal is interbedded with various carbonaceous and shale units. Proximate and ultimate analyses as well as calorific tests show that the coal has a calorific value between 3500 and 4100 kcal/kg, with 35% ash and 10% moisture. Fixed carbon, volatile matter, and sulfur contents are 54.2% (daf), 45.8% (daf), and 1.2%, respectively. Petrographic properties of the coal seam show that it has 0.51% maximum reflectance (Rmax), 76% total huminite, 7% liptinite, and 5% inertinite. In addition to the organic part, the coal has 3% pyrite and 9% other inorganics that contain clay, quartz, and calcite [18].

3. Pilot area selected for modeling

In order to characterize the coal mined in the Yeni Celtek underground operation, numerical reservoir simulations of gas emissions into ventilation systems were evaluated. For this purpose, a pilot area within the mine was selected. The entire operation and the selected pilot area are shown in Figs. 3 and 4, respectively. This pilot area was selected because the area was far from panel operations and thus was not affected by instantaneous changes in methane emissions, and also because the planar view to be used in grid-building contained both intake and return airways and ventilation monitoring stations (Figs. 3 and 4).

Ventilation airflow rates, areas of entries, and methane percentages were measured at 16 different locations in intake and return airways throughout the mine. In addition to airflows, average ventilation pressures in the return airways were also recorded. Out of these 16 locations, seven monitoring stations were within or were in very close proximity to the selected pilot region of the mine.

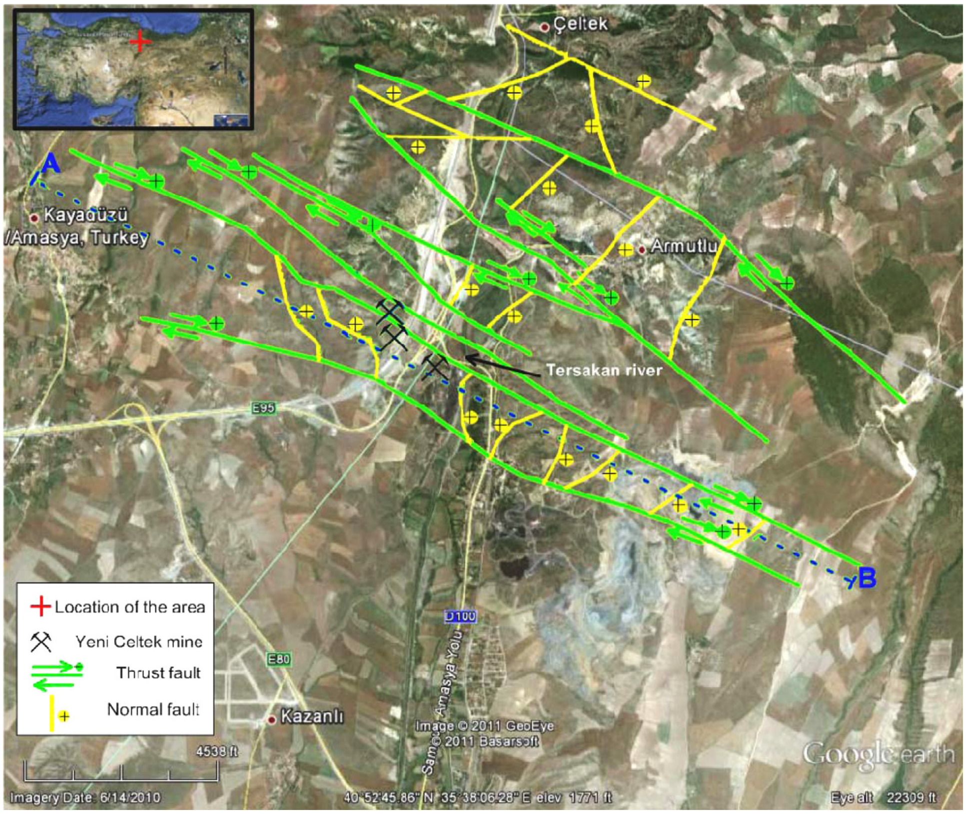

Fig. 1. Location of the Yeni Celtek mine and structural map showing faulting in the area.

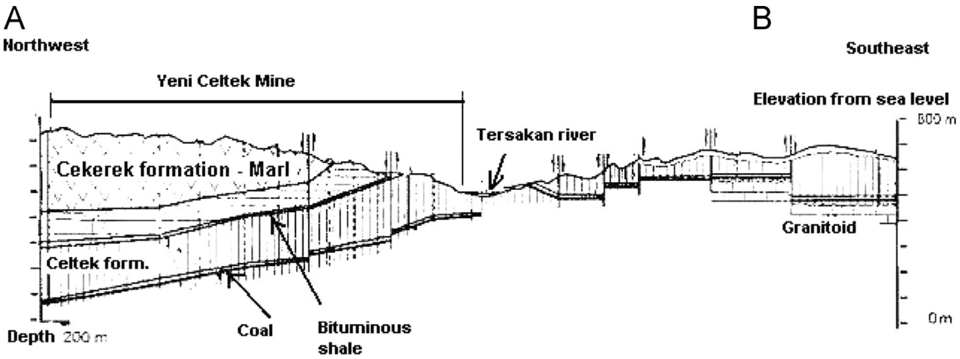

Fig. 2. Geological cross section along the A–B profile shown in Fig. 1. (Modified from [19]).

Fig. 5 shows various measurements recorded and calculated in intake and return entries at different dates at the monitoring stations shown in Fig. 4. Fig. 5-A and -B shows ventilation rates and velocities, calculated based on the areas. These figures show that Stations 3 and 4, which were in the same line, had approximately 1200 m^3/min flow before the return split into two. Thus, Station 1 in the return recorded ~600 m^3/min in return air, and the rest of air flow went to the other branch after split. On the intake side; each of the Stations 5, 7, and 8 (7 and 8 were in the same line) measured approximately 600 m^3/min, respectively. Thus the total intake flow rate provided at Station 6 was ~1200 m^3/min.

Methane percentages in the ventilation air were also measured at return stations. The measurements showed that the air had ~0.5%-0.6% methane. Using measured methane percentages and air rates, methane emission rates (or methane rates) were calculated. These data are shown below in Fig. 5-D. Rate data presented in this figure show that methane passed through Stations 3 and 4 at a rate of ~7 m^3/min. The rate of methane flow at Station 1, on the other hand, was between 2 and 3 m^3/min. Air and methane flow rates at Station 1 suggest that the split of return actually divided air and methane quantities into approximately two. This was an important consideration in building the conceptual model for numerical modeling.

Fig. 5-C shows average ventilation pressures measured in return entries at different dates. The data show that the pressures changed between 97 and 99 kPa. The pressure data can be considered relatively steady and fluctuated within a range of 2 kPa, possibly due to ventilation controls in the mine. Although the fluctuation in ventilation air pressure was small, this variation in pressure may affect methane release from the coal bed. These kinds of fluctuations have been observed in coal mines due to variations in atmospheric pressure [20]. An examination of methane flow rate together with average ventilation pressure shown in Fig. 5-C indicates that methane flow rate correlated with changes in the ventilation pressure. These figures demonstrate the importance of

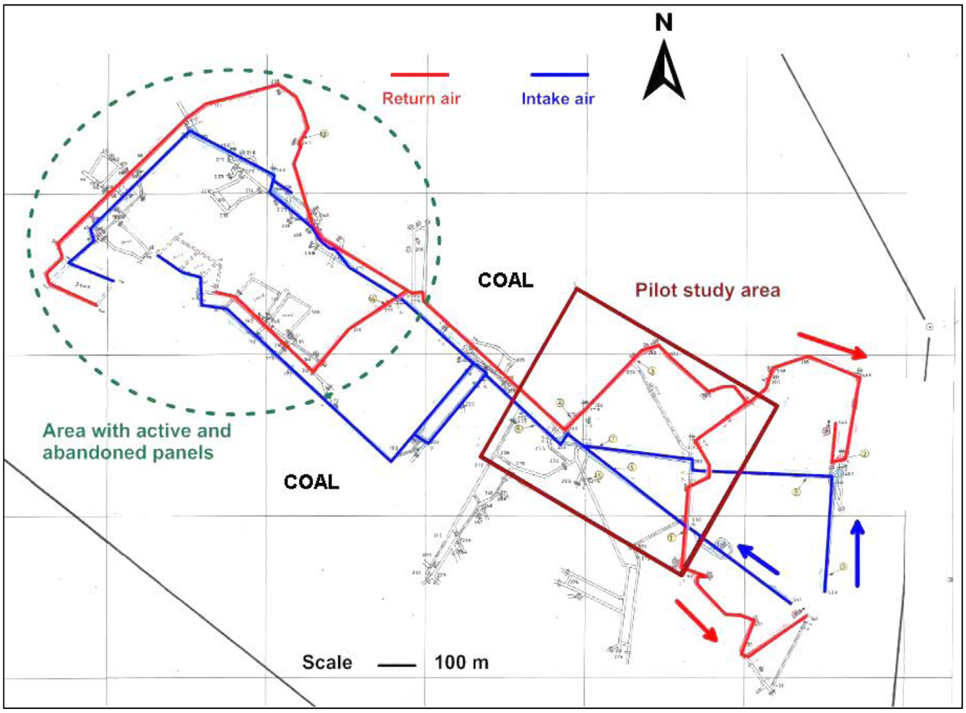

Fig. 3. Yeni Celtek mine plan and ventilation air paths, in which uncolored sections were separated by seals and doors. Because of this separation, the uncolored areas were not considered to be part of the active ventilation for the purposes of this study. In this figure, the locations of active and abandoned panels, as well as location of the pilot study area, are also shown.

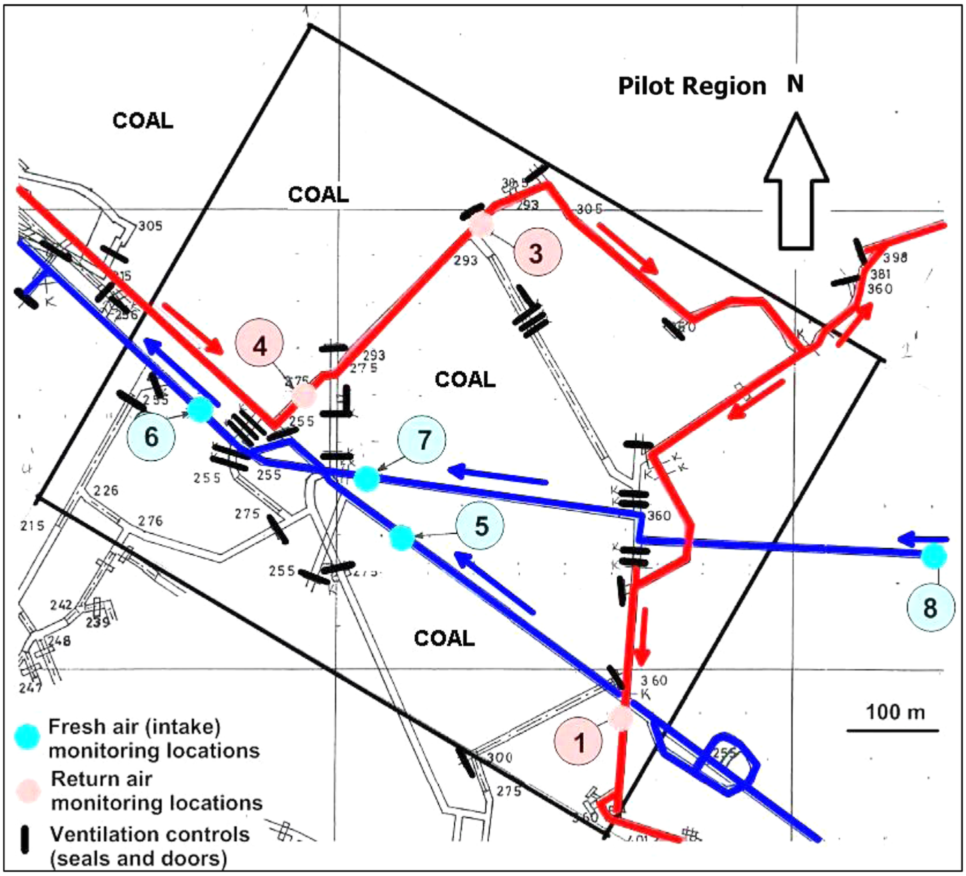

Fig. 4. Expanded view of the selected pilot study area showing details of ventilation controls and monitoring points. As indicated in this figure, Stations 1, 3, and 4 were in return entries and 5, 6, 7, and 8 were in intake entries.

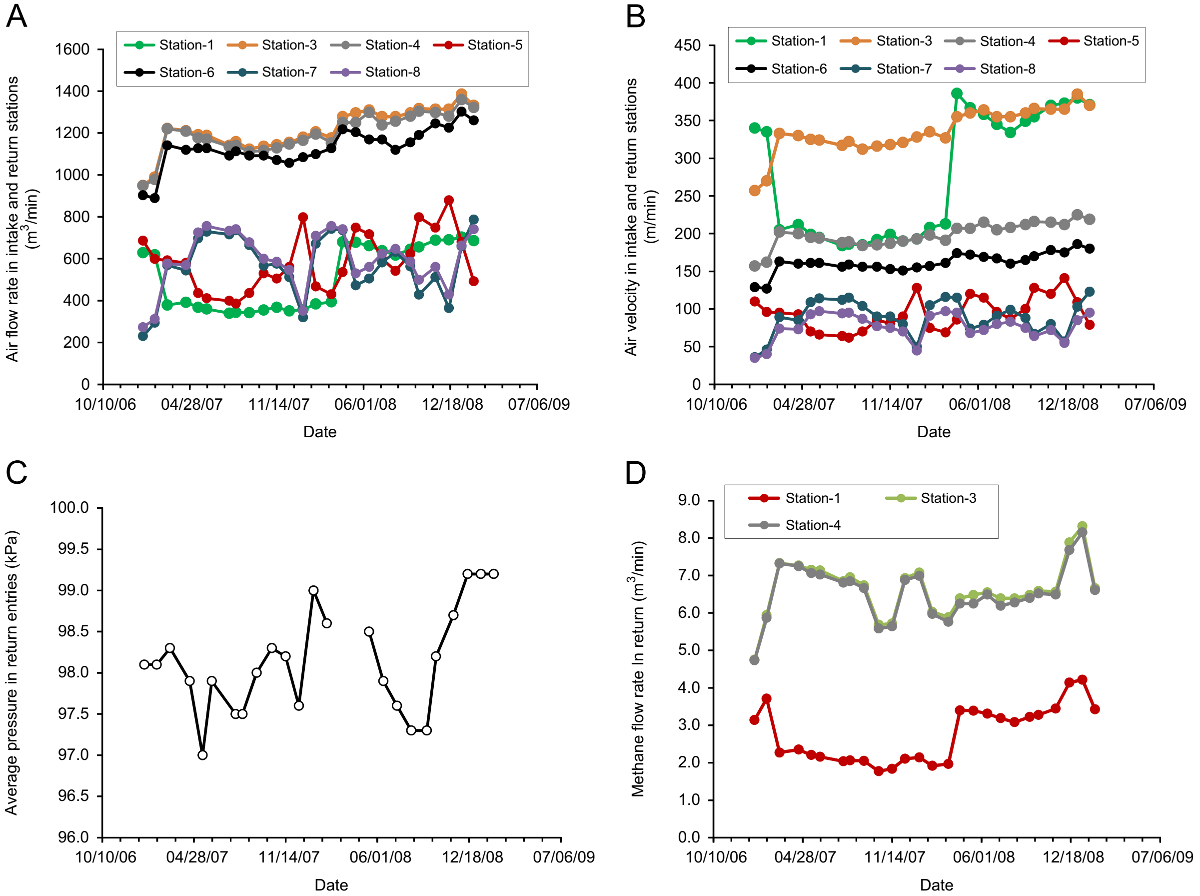

Fig. 5. Ventilation data measured in intake and return airways in the Yeni Celtek mine. A—Airflow measured at monitoring stations; B—Air velocities calculated for monitoring locations; C—Average ventilation pressure measured in return entries and D—Methane flow rates calculated for monitoring location in return entries using measured methane concentration data.

evaluating pressures with methane rates, as variations in ventilation pressures may affect gas flowing into and out of the sealed gobs, into the active workings, and into the return airways.

4. Methodology and model building

Grid-based numerical modeling techniques, such as reservoir models and computational fluid dynamics (CFD) models, are "non-classical" alternatives to the network-based models in ventilation engineering. They consider the mining environment as a volume rather than as one-dimensional ventilation "network" branches. Different mining-related geometries with varying transport properties can be created within the simulation volume. They also can model a wide range of processes, boundary conditions, and parameters, as well as unsteady state situations, which makes them advantageous compared to conventional approaches in ventilation design and gas management [21].

In order to estimate reservoir properties of the coal seam being mined in the Yeni Celtek mine, a base coal bed reservoir model was constructed for the selected pilot region, and the data shown in Fig. 5 were used as history matching and model constraint parameters. The base model was built using Computer Modeling Group's Generalized Equation of State Model (GEM) with dual porosity formulation [22]. A Gilman and Kazemi type shape factor was preferred for dual-porosity unsteady state gas transport. The coal bed model in this study contained gas and immobile water due to absence of water flowing into the entries. Porosity and permeability changes due to matrix shrinkage and swelling effects were neglected. This assumption is due to the fact that the exposed area of the coal seam lies within the entries, which is a large area in the pilot region. Therefore, the effects of swelling and shrinkage would be minimal. In addition, stresses that would cause porosity and permeability to change due to gas desorption would be minimal, compared to stresses concentrated around mine intake and return entries as well. Furthermore, for the purposes of modeling coal was assumed saturated and gas storage

Table 1
Values of the matrix and fracture properties of coal and the return entry in the base model.

Parameter	Matrix		Fracture	
	Coal	Return entry	Coal	Return entry
Permeability, *x*, md	0.0001	10	4	1.0E+9
Permeability, *y*, md	0.0001	10	4	1.0E+9
Permeability, *z*, md	0.0001	10	1	1.0E+9
Porosity, fraction	0.0005	0.1	0.02	0.99
Fracture spacing, *x*, m	–	–	0.50	0.1
Fracture spacing, *y*, m	–	–	0.25	0.1
Fracture spacing, *z*, m	–	–	0.10	0.10
Water saturation, fraction	0.05	0.05	0.20	0.01
Pressure, kPa	517	–	517	–
Coal density, kg/m^3	1435	–	–	–
Langmuir volume, m^3/ton	6.24	–	–	–
Langmuir pressure, kPa	1034			
Gas content @ 517 kPa, m^3/ton	2.08			
Desorption time, days	100			

in and desorption from coal followed the Langmuir-type isotherm. This assumption follows the Langmuir-like gas adsorption–desorption process in coal at constant temperature, which is a widely accepted assumption for coal for modeling purposes. Also, since mining in this coal seam started prior to the data collection in the study, saturation prevailed and desorption followed the saturation curve (Langmuir isotherm).

This 3-D model was built with two layers to reflect spatial descriptions of mine details, i.e. entries and locations of monitoring stations in intakes and returns. The selected region was represented with Cartesian grids with $204 \times 206 \times 2$ grids in x, y, and z directions, respectively. Square grids with 3-m × 3-m sizes in x and y directions were used. The x- and y-sizes of grids were determined based on the widths of entries, which were ~3 m. The thicknesses of layers were 2 and 3 m for roof coal and for the mining layer, respectively.

Reservoir simulators are "porosity" models. In other words, there has to be porosity defined for each grid regardless of whether it is an empty flow channel or a porous media. This aspect of reservoir models is different than computational fluid dynamics (CFD) models, where it is possible to define 100% porosity and infinite permeability at any location. However, as a trade-off, reservoir models are more accurate in simulating flow in porous media. Therefore, the advantages of both types of models were tried by formulating both the coal seam and the ventilation entries as dual-porosity systems. In this formulation, return entries were modeled as proxy "void" spaces in the lower grid layer by assigning them the maximum permeability (1.0 E +9 md) and porosity (99%) values allowed in the simulator. Coal-related parameters were set so there would be no gas storage and diffusive flux within the entries. This treatment allowed very high permeability in entries, with some remaining resistance due to a finite permeability value. Dual-porosity formulations were used throughout the model and, as it was not possible to assign different options in various locations within the grid model, each coal- and entry-grid had both matrix and fracture properties. For construction of the base model, the values of matrix and fracture properties were assigned based on experience and based on both unpublished and published reports of coal properties of the Yeni Celtek mine and the stratigraphy of the area in general [23,24]. The properties of the base model are given in Table 1.

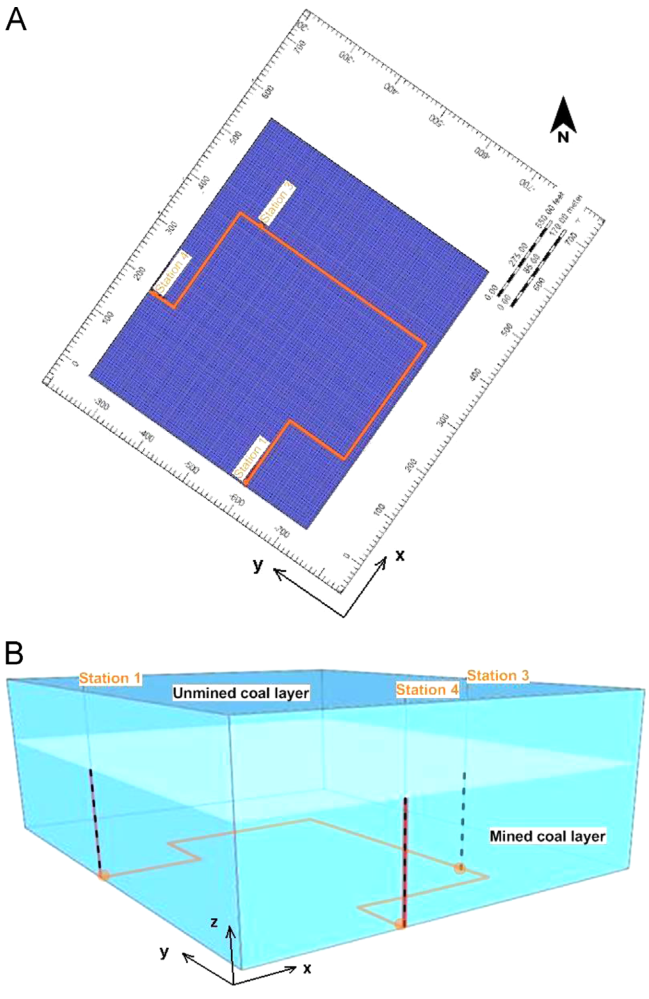

Fig. 6. Mining (lower) layer of simulation grid (A) and the 3-D view of entire model (B). Vertical axis in B is not to the scale.

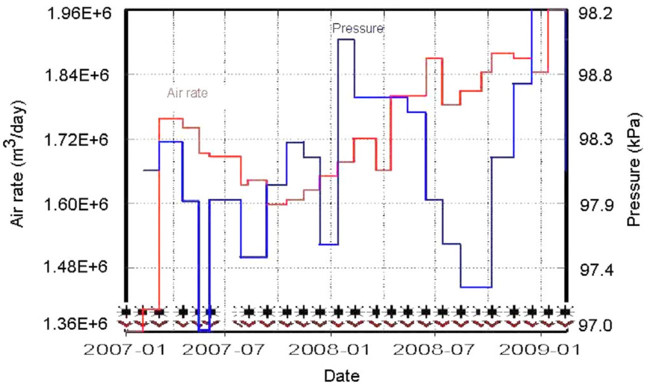

Fig. 7. Rate and pressure constraints of Station 4 during the test run.

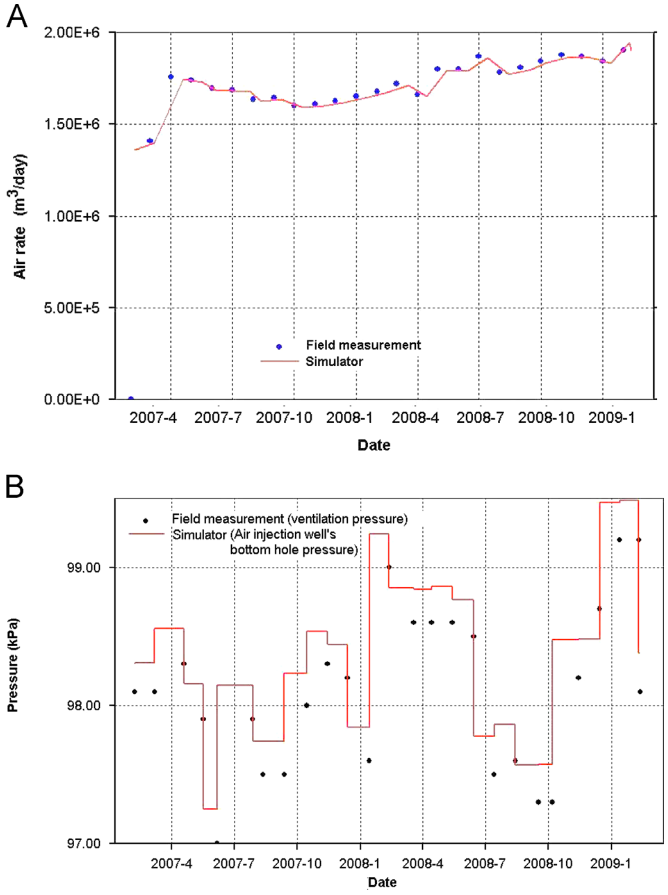

Fig. 8. Field data and simulated values of rate (A) and pressure (B) for Station 4 in the numerical model.

In the model, wellbores were proxy for monitoring stations. They were connected to grids with negative skins for improve flow in and out. Intake air, which was modeled by nitrogen (N_2), was provided with an injection well at the Station 4 location, whereas monitoring of return air was modeled by two vertical production wells at Stations 1 and 3. However, since Station 4 was on the return entry and the air was not completely free from methane at that location, composition of injected gas was set as 0.5% methane and 99.5% N_2. The percentage of methane in the injected air was based on the actual average methane concentration in the mine air. Also, due to approximate symmetry in flow quantities presented in previous section, the branch of the return split opposite to Station 1 was not represented in the model based on the judgment that Station 1 would withdraw air and methane quantities in accordance with the ventilation pressure prevailing at that point.

Recurrent operation data of these wells were coded based on the actual monitoring times given in Fig. 5. The intake well at Station 4 was operated with flow conditions with injection pressure calculated by the model. Production wells at monitoring locations (Stations 1 and 3), on the other hand, were operated with bottom-hole pressure conditions equivalent to ventilation pressure, and methane flow rates were calculated by the simulator.

Use of a Cartesian grid system simplifies grid building and shortens computational time significantly. However, it may make the modeling of non-orthogonal structures within the reservoir more difficult. This was the case when modeling the return entry shown in Fig. 4. In order to model the return entry within the grid system and also to realistically simulate gas inflow from the surrounding coal, its shape was modified for orthogonal corners while keeping its length the same as it was in the mine. This would maintain the surface area of the modeled portion of the return line the same for potential methane emissions from sides and from the upper unmined coal layer. The mining layer of simulation grid and its 3-D visualization with monitoring stations are given in Fig. 6-A and -B, respectively.

5. Results and discussion

The total simulation time for base model runs and parametric runs for history matching of ventilation methane data was 766 days. Before starting the history match process of monitoring locations at Stations 1 and 3, air rate and bottom-hole pressure of Station 4 were tested with base coal seam parameters given in Table 1. For this test, the injection well constraint was set at the air rates reported for Station 4 and bottom-hole pressures were calculated. This test showed whether intended injection rates could be achieved at the pressure conditions in the entries.

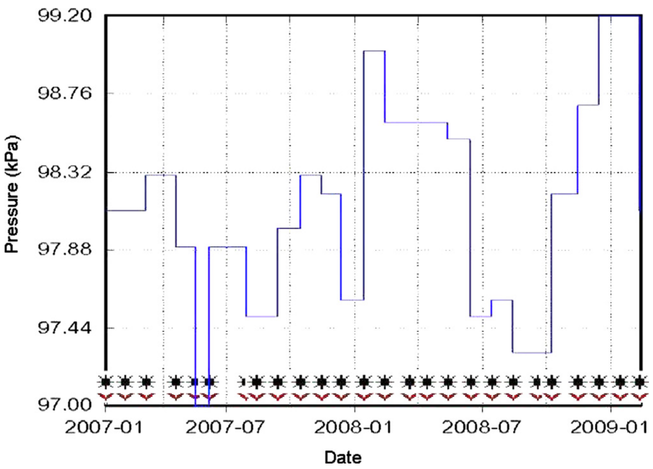

Fig. 9. Pressure constraints of monitoring Stations 1 and 3 during their operation in base run and history matching runs.

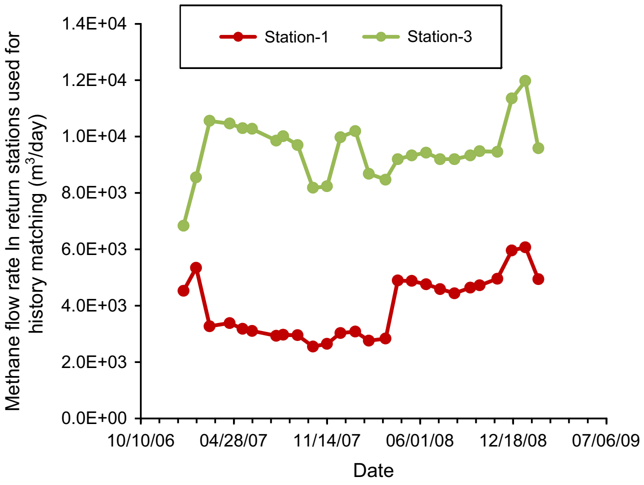

Fig. 10. History matching data at Stations 1 and 3 to estimate coal reservoir properties.

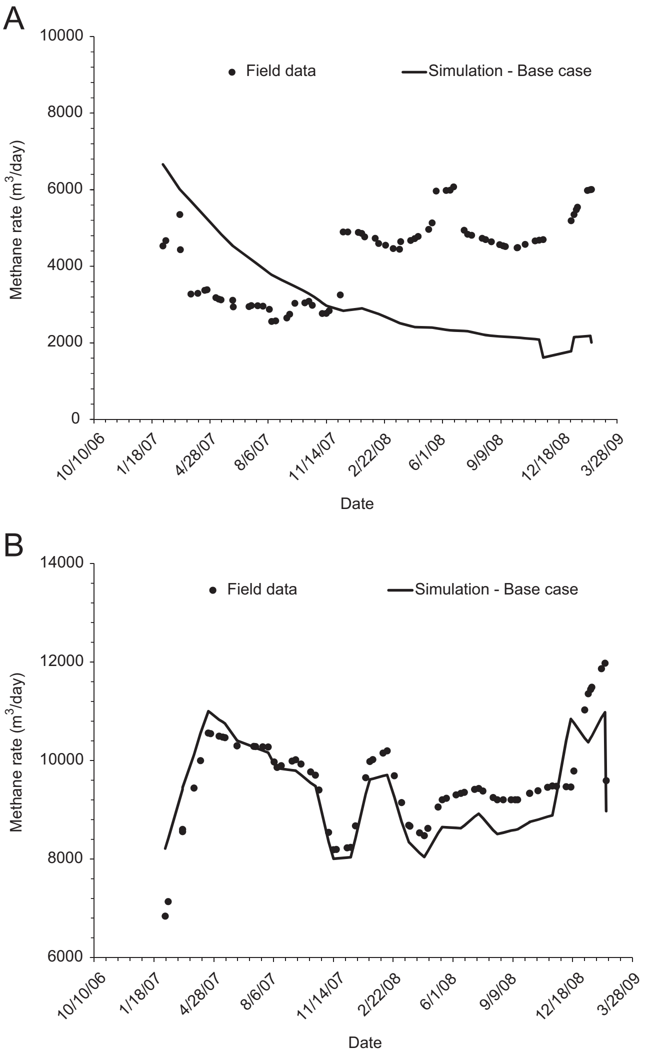

Fig. 11. History match of simulation results with the field masurements for Station 1 (A) and Station 3 (B) using base properties of the coal seam as given in Table 1.

Constraints at Station 4 with recurrent dates of operation marked are given in Fig. 7. The results of airflow and pressure calculation runs are given in Fig. 8-A and -B, respectively.

Fig. 8-A and -B shows that airflows at Station 4 could be reproduced very closely, and that computed pressures were within a 0.2 kPa interval. This shows that assigning high permeabilities and porosities to return entries made it possible to inject gas with very high rates as required in a mine's ventilation system. However, due to finite permeabilities that had to be assigned to infinite-permeability locations, there was still some resistance in the entries, which caused a little higher-than-measured pressure at the injection point. Nevertheless, for practical purposes, a 0.1–0.2 kPa difference in pressure was acceptable for using these rates and pressures as boundary conditions at the Station 4 location in the ventilation return entry.

For base run and for history matching of methane measurements at Stations 1 and 3, the wells that proxy the observation points were operated with bottom-hole-pressure constraints given in Fig. 9, which was equivalent to the field measurements in Fig. 8-B with its marked recurrent events during operation. In this process, the same pressure constraints were defined at both locations as only average pressure readings, rather than separate data, were available for each station. While monitoring stations were operating with the pressure constraints to deliver air from return entries, methane rates were computed based on the composition to match the field data given in Fig. 10 for Stations 1 and 3.

The results of computed methane flow rates in return entries using base coal parameters are given in Fig. 11-A and -B for Stations 1 and 3, respectively. These plots also show the measured data that compare simulations with field measurements. Results show that simulation using base coal seam properties could successfully model the measurements in Station 3, while the simulated data for Station 1 showed a constantly declining rate, which was not the case in field measurements. Although varying methane flows in field measurements of these stations might be partly due to changing the settings of ventilation controls within the pilot area, such as flow area through ventilation doors and leakages through stoppings, the discrepancy between simulated results and measurements could likely be due to mismatch of base reservoir properties. In order to improve the history match of simulations for Stations 1 and 3, a set of coal seam properties were systematically changed and simulations were repeated.

Coal, as a sorptive dual-porosity "rock," has many parameters that can be included in simulations and can be changed for history matching purposes. However, some of the parameters are more

Table 2
Coal seam parameters and their varied values between simulation cases for history matching of methane rates at Stations 1 and 3.

	Base case			Case 1			Case 2		
	x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
Cleat permeability, md	4	4	1	**0.1**	**0.1**	**0.01**	**6**	**4**	**1**
Fracture spacing, m	0.5	0.25	0.1	0.5	0.25	0.1	0.5	0.25	0.1
Desorption time, days	100			100			100		
Langmuir pressure, kPa	1034			1034			1034		
Langmuir volume, m^3/ton	6.24			6.24			6.24		
	Case 3			Case 4			Case 5		
	x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
Cleat permeability, md	**3**	**1**	**1**	3	**1**	**0.15**	3	1	0.15
Fracture spacing, m	0.5	0.25	0.1	0.5	0.25	0.1	0.5	0.25	0.1
Desorption time, days	100			100			300		
Langmuir pressure, kPa	1034			1034			1034		
Langmuir volume, m^3/ton	6.24			6.24			6.24		
	Case 6			Case 7			Case 8		
	x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
Cleat permeability, md	**4**	**6**	**1**	**5**	**4**	**1**	5	4	1
Fracture spacing, m	0.5	0.25	0.1	**0.8**	**0.4**	**0.1**	0.8	0.4	0.1
Desorption time, days	300			**400**			400		
Langmuir pressure, kPa	1034			1034			**1500**		
Langmuir volume, m^3/ton	6.24			6.24			6.24		
	Case 9			Case 10			Case 11		
	x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
Cleat permeability, md	5	4	1	5	4	1	5	4	1
Fracture spacing, m	0.8	0.4	0.1	0.8	0.4	0.1	0.8	0.4	0.1
Desorption time, days	400			400			400		
Langmuir pressure, kPa	1034			**2000**			**2500**		
Langmuir volume, m^3/ton	**5**			**6.24**			**6**		
	Case 12			Case 13					
	x	*y*	*z*	*x*	*y*	*z*			
Cleat permeability, md	5	4	1	5	4	1			
Fracture spacing, m	0.8	0.4	0.1	0.8	0.4	0.1			
Desorption time, days	400			400					
Langmuir pressure, kPa	**2000**			**2500**					
Langmuir volume, m^3/ton	**5**			**7.5**					

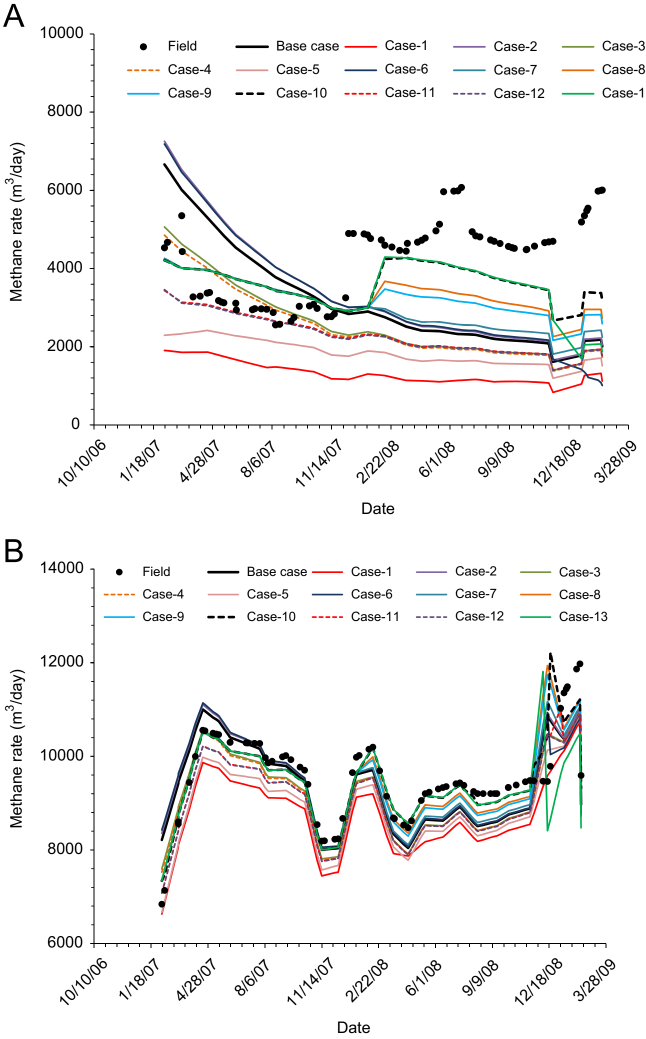

Fig. 12. History match results of methane rate simulated for Stations 1 and 3 for the return entry using the parametric cases given in Table 2.

basic in terms of their relevance to coal seam desorption and gas production, and their influence can outperform the other variables when changed in simulation runs. Thus, such basic parameters that are of most importance to coal seams were considered and changed as part of the parametric study to history match the simulation results to methane rate measurements in Stations 1 and 3. These parameters were fracture (cleat) permeability, Langmuir sorption terms, desorption time constant, and fracture (cleat) spacing.

In coal beds, vertical permeability is usually significantly lower than horizontal permeability because of the presence of bedding. Thus, horizontal permeability and its direction (anisotropy) are more important in coal bed reservoirs. Horizontal permeability and its anisotropy in coal beds are characterized with face and butt cleat permeabilities, which are in N–S and E–W directions, respectively, in this area. The presence, or lack, and direction of permeability have a profound effect on methane inflow. Direction and magnitude of permeability is important to quantify methane emissions during mining and migration into ventilation entries. When face cleats, where permeability is higher, are perpendicular to entries, more gas is emitted into mine workings.

Furthermore, the major portion of the coal seam gas exists in the adsorbed state rather than in a free state. Adsorption and desorption of methane from coal is controlled by the shape of the Langmuir isotherm, which defines the relationship of coal bed pressure to the capacity of a given coal to hold gas at a constant temperature. In a numerical simulation context, the Langmuir equation provides a necessary boundary condition at the matrix-cleat interface. Thus, the shape of the Langmuir isotherm is important for manipulating the boundary condition between matrix and cleats and for controlling desorption of gas from coal. The shape of the isotherm is largely affected by V_L and P_L, the Langmuir volume and Langmuir pressure, respectively. These two quantities dictate the gas content of the coal at a certain cleat pressure and the gas release rate as pressure decreases. Since coal bed pressure is related directly to the methane content, higher pressure results in higher methane inflow rates at constant values of V_L and P_L. Since base run results showed enough methane flowing at the monitoring locations, coal pressure was not changed and V_L and P_L were varied for history matching.

The next set of parameters varied in the simulation cases were desorption time and fracture spacing. Desorption time controls unsteady-state diffusion in microporous medium. The desorption time constant is proportional to the square of cleat spacing and inversely proportional to diffusion constant. In effect, desorption time is the time constant that regulates the rate at which gas is released from the micropores into the macropore system. For its small values, the diffusion process is faster. Likewise, small values of fracture spacing create small desorption time constants to generate the same effect [11].

Varied coal seam parameters compared to base parameters and their values pertinent to each simulation case are given in bold in Table 2. Results of parametric cases for history matching are given in Fig. 12-A and -B for Stations 1 and 3, respectively. These data show that some of the cases resulted in worse results in terms of matching methane rates in monitoring stations while others improved significantly compared to base results. More specifically, Cases 8, 10, and 13 seemed to provide the best results. These cases included both increasing Langmuir volume and pressure as well as desorption time. Langmuir volume and pressure manipulate the amount of gas stored in the coal and its rate of desorption, while desorption time controls the diffusion process between matrix and fractures.

Although visual inspection of the data given in Fig. 12 and making a decision regarding the estimated coal properties based on these inspections can be possible, a better approach explores the mean squared (MSE) and root mean squared errors (RMSE) between simulation runs and field data to find the best match. Fig. 13-A and -B give the mean squared and root mean squared errors between simulation cases and field measurements for Stations 1 and 3, respectively. Based on the error calculations of methane flow rates in monitoring stations and simulations, Case 10 produces the least error. In this case run, the RMSE and MSE were 1204.9 m^3/day and 1.45E+6 m^3/day, respectively, for Station 1. The RMSE and MSE were 404.9 m^3/day and 1.64E+5 m^3/day, respectively, for Station 3.

Using the results of history matching runs, the estimated coal parameters of the coal seam mined in the Yeni Celtek mine can be given as an updated version of Table 1 and are shown in Table 3. In considering these parameters, it should be stressed that the results of reservoir simulation may not be unique and that there may be other parameters that can be varied to obtain the same results. This is the nature of all simulation studies, with the results best judged by experts and in the context of supporting field data. In this respect, this study is presented primarily as a demonstration of an approach that combines coal seam reservoir simulation with mine ventilation engineering in an effort to better control methane in coal mines and to produce it effectively from active and abandoned mines through estimation of coal seam properties.

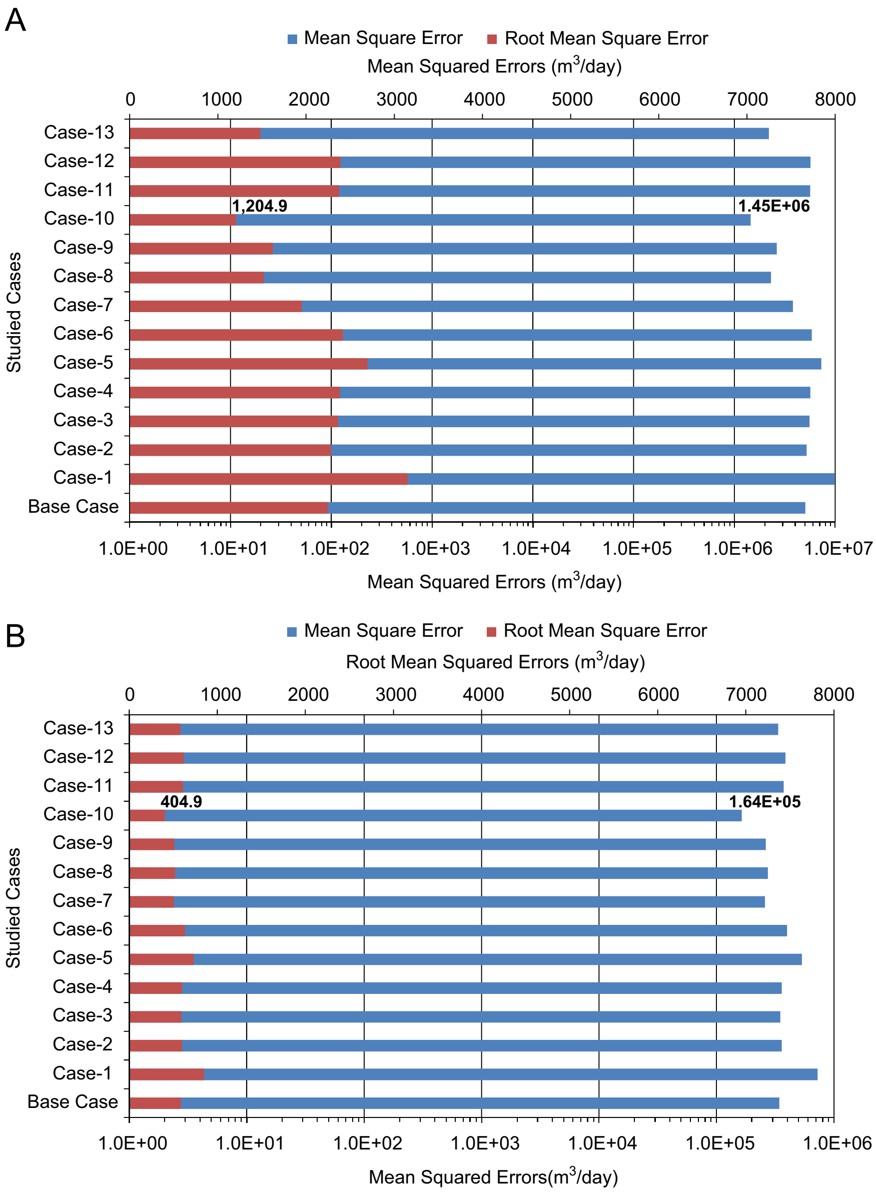

Fig. 13. Mean squared (MSE) and root mean squared (RMSE) errors calculated between simulation results and field measurements for different cases.

Table 3
Reservoir parameters estimated through reservoir simulation and ventilation methane data for the coal mined in the Yeni Celtek mine.

	Coal	
Parameter	Matrix	Fracture
Permeability, *x*, md	0.0001	5
Permeability, *y*, md	0.0001	4
Permeability, *z*, md	0.0001	1
Porosity, fraction	0.0005	0.02
Fracture spacing, *x*, m	–	0.80
Fracture spacing, *y*, m	–	0.40
Fracture spacing, *z*, m	–	0.10
Water saturation, fraction	0.05	0.20
Pressure, kPa	517	517
Coal density, kg/m^3	1435	–
Langmuir volume, m^3/ton	6.24	–
Langmuir pressure, kPa	2000	–
Gas content @ 517 kPa, m^3/ton	1.28	–
Desorption time, days	400	

6. Summary and conclusions

This study showed the potential use of ventilation air measurements regularly monitored in underground coal mines coupled with numerical reservoir simulation. The work utilized readily available ventilation data as inputs to numerical simulation to estimate coal seam reservoir properties.

A three-dimensional coalbed methane reservoir model was constructed for the Yeni Celtek mine, Turkey, from which ventilation data were obtained. Two of the ventilation monitoring stations in return airways were utilized as history matching points, and methane flow rates through these stations were used as history matching parameters. To match measured and predicted methane rates at these locations, several coal seam reservoir parameters were varied.

Results showed that cleat permeabilities, desorption time, and Langmuir parameters were the controlling parameters affecting methane liberation into return airways in the coal mine. Prediction error tests using mean squared error and root mean squared error showed that the changes made to the base case parameters by Case 10 in Table 2 provided the best results. However, results of reservoir simulation may not be unique. Other parameters can also be varied in the simulations for history matching purposes. Although coal parameter changes made by Case 10 gave the best estimate, the values should be confirmed with well test interpretations or field production data, if available, for more accurate results of reservoir properties of the coal seam.

Characterization of coal seam reservoir properties is an important step for planning degasification and coal mine methane production and utilization. To this end, this study is presented primarily as a demonstration that combines coal seam reservoir simulation with mine ventilation engineering.

Disclaimer

The findings and conclusions in this paper are those of the authors, but do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company name, product, or software does not constitute endorsed by NIOSH.

Acknowledgments

Authors are grateful to TKI (Turkish Coal Enterprises) and Yeni Celtek Mine for their help and technical support in obtaining mine and ventilation data.

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