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CFD Modeling of Impact of Gas Content Uncertainty on Methane Distribution in Underground Coal Mine Roadways

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Abstract

Methane has been known as a safety risk for the coal mining activities. Accordingly, one can mitigate this risk, and hence, the level of hazard to which the mining workers are exposed, by predicting the possible exceedance of allowable methane dosage should be provided with a reliable information on the distribution of methane across the working face considering the uncertainties associated with the gas content of such deposits. In this work, the gas content uncertainty in a coal seam is first investigated using the geo-statistical simulation. Then a method is proposed in order to predict methane gas emission based on the Monte Carlo random simulation method. Next, the results obtained are introduced into a 3D Computational Fluid Dynamics (CFD) model to estimate the methane distribution considering the uncertainty associated with the gas content. Defined as zones where the methane concentration is so high that an explosion is much likely to occur, the elevated methane zones (EMZs) are delineated across the working faces. The results obtained show that UGC has an impact on the ventilation parameters and EMZs. The proposed method could be carried out in order to guide the ventilation design in improving safety.

1. Introduction

The methane gas emission and dispersion assessment serves as an advantageous foundation for a mining design in terms of ventilation requirements for an adequate gas management and prevention. This, in turn, will greatly mitigate the risk of possible gas explosions, thereby leveling up the coal mining safety [1].

Boosting the risk of methane explosion inside coal mines, the methane gas content of coal strata has long been seen as a major threat to the underground mining activities. As a mitigation tool, the mine ventilation systems have been developed to retain the gas concentration below a certain allowable threshold (also known as explosive limit). As the methane gas is being accumulated within an underground mine space, an elevated methane zone (EMZ) may be established within localities where air flow is inadequate. Should the accumulation continue, the gas concentration may exceed the explosive limit (5-15%), in which case the methane is highly susceptible to ignition, upon coming in contact with an ignition agent, resulting in an abrupt explosion followed by combustion of the coal dust. In order to address this requirement, a mining operator must be provided with as much reliable as possible data on the distribution of methane gas across the working face of the mine to formulate strategies for the methane accumulation control properly. Gas accumulation

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in an underground mining space is known to be controlled by the quality of ventilation and the gas emission rate into the working face of the mine, to name the most important factors. Methane may emit out through the seams developed in the coal bed and/or nearby gas-bearing rock masses upon coal mining activities as such activities tend to disturb the stress balance in rock bodies. The flow of the methane gas into the working face of a mine is controlled by, among other factors, the shape and dimensions of the gas emission area, gas content of the seams, methane emission rate, and how intensively the mine is being operated [2]. Given that the methane gas flow into the mine shall is in some way compensated for by ventilation, proper ventilation systems contribute to higher levels of mining productivity and safety at lower energy and operational costs. With the methane gas emission being determined by various factors in terms of geology, geography, and mining operation, it is extremely complicated to have it properly forecasted prior to actual mining, placing an emphasis on the paramount importance of the mentioned factors in sub-surface mining. On the other hand, the gas emission imposes significant impacts on the performance of the mine ventilation system [1].

It is thus necessary to use an accurate method for estimating the gas content in a coal mine before commencing the mining operation. The accurate prediction of the gas content of coal layers is a must for ensuring the appropriate ventilation and safety in a coal mine. Despite the essential role played by the gas content estimation in the determination of the appropriate ventilation system, it is an extremely complex task to perform due to the wide differences in the gas content characteristics and the lack of adequate datasets. Basically, the uncertainty is obtained upon an appropriate modeling and structural analysis. The gas content is usually evaluated based on the confined gas volume per unit mass of coal rock and errors of estimation using the direct method are evaluated [3]. The gas content measurement is usually accomplished through the desorption analysis in order to achieve either of the two following important objectives [4]:

1. Assess the volume of coalbed methane for economic evaluations, and/or
2. Evaluate the gas volume released upon distribution of coalbed through sub-surface mining for risk assessment.

In both cases, the aim of gas content assessment is to evaluate the gas in place (GIP) stored within the coalbed provided that this gas content is normally lower than the total storable gas in the coalbed [4]. The *in-situ* coal gas content is dependent on many geological, geo-chemical, hydrogeological, and biological processes. Coal is an inherently heterogeneous material, and therefore, has variable gas storage reservoir properties. There can be substantial variability in gas content in a coal deposit in a spatial and stratigraphic manner and also within the samples from a single seam in a single drill hole.

2. Literature review

As a basic safety practice, one must estimate the gas content of coal seam, and proceed to predict methane emission into the mine. In the 1950s, some methods and processes were presented in order to measure the gas content of coal seams, and the statistical methods were used to calculate and predict the gas content and gas emission in coal mines. A handful of geo-statistical methods have been used to estimate the gas content. In this context, the geo-statistical methods and modeling provide unique models for the spatial correlation of the sampled data to integrate the available pieces of information for the accurate assessment of the uncertainty associated with different traits in question [5]. Hohn and Neal [6] have used the geo-statistical analysis for estimating the gas content of the Devonian shales in the West Virginia. In another work, Olea *et al.* [7] have followed the geo-statistical method presented for evaluating the uncertainty associated with the assessment of coal reserve, and further applied the proposed technique for a lignite orebody in Texas.

The geo-statistical technique can be applied to handle different types of data with various resolutions, qualities, and associated uncertainties to match different data at different scales and to establish geologically heterogeneous models [8]. Then the data and the corresponding models could be used as the input to solve the dynamic problems including the flow model. Karacan *et al.* [9] have used the Sequential

Gaussian Simulation (SGSIM) to model the emission of methane gas and GIP in a geo-statistical manner. Later on, Zhou *et al*. [10] have focused on SGSIM to model the CBM sources. For the stochastic analysis of the CBM, they used a total of 71 data points acquired from 6 boreholes across the Qinshui Basin, southern China. The borehole-acquired and experimental data was utilized for the prediction of the coalbed thickness, gas content, and ash content. The methane source model was then constructed based on the coalbed thickness, quality, and gas content. In his work, Karacan has investigated the effectiveness of what he referred to as gob gas ventholes (GGVs) that were constructed along a longwall panel for controlling methane emission, and hence, preventing inundation of the mining ventilation system [11]. Later, Zhou and Guan [12] modeled the uncertainty associated with the estimation of CBM reserves using a multivariate regression method and also the Gaussian simulation, and the results obtained indicated that both methods produced the same output.

In the 1980s, various methods were proposed in order to predict gas emission. Since then, the analog method, geological mathematical model, speed method, and other methods of predicting gas emission have been proposed and used. All new methods and technologies provided a scientific basis for the mine design and reconstruction [13]. Numerous researchers have reported the use of Monte Carlo simulations for modeling methane gas emission, with the results compared to those of stochastic modeling to reflect the acceptability of the simulation results [14]. However, as coal gas is a complex phenomenon, the research to predict gas content and gas emissions has not yet reached a consensus, and no mature theory or accurate calculation method has been recognized so far.

Lots of studies have reported on gas distribution across working face of mines. In early 1990s, Heerden and Sullivan [15] presented a work where they explained the gas flow and ventilation patterns using CFD, for the first time, in a heading development. Just after that, Srinivasa [16] has simulated air velocity distribution across a longwall face by means of a 3D CFD scheme. Later on, Edwards *et al*. [17] have presented a general CFD-based simulation process to model the ventilation flow patterns in a heading, demonstrating the promising capabilities of CFD for addressing mine safety and health issues. Many other scholars have undertaken to simulate ventilation and/or methane (or another gas) emission in headings/drivages [18-25] and to investigate longwall goaf gas flow properties through CFD simulations [26-28]. Zheng and Tien have odeled [29] the characteristics of methane flow on a longwall face by taking into consideration different sources of methane emission: broken pieces of coal by the shearer, coal fragments on conveyor, coal ribs and the coal on the belt. Lately, a series of full-scale 3D longwall models were built by Ren and Wang [30], who let their models represent a primary longwall equipment. They then studied the flow behaviors of the ventilation air, emitted gas, and/or generated dust considering the effects of cutting sequence and shearer position. Cheng *et al*. [31] have used the Computational Fluid Dynamics (CFD) simulation for managing gas hazards and fire risk in underground coal mines. Adopting an auxiliary ventilation system, Hasheminasab *et al*. [32] have approximated the methane distribution across a coal mine face to demonstrate the effectiveness of such an auxiliary system for mitigating the risk of the emission of methane gas and/or other pollutants at the working face of the mine. Rahimi *et al*. [33] have modeled the impact of the uncertainty associated with the gas emission on the distribution of the required airflow rate. The result showed that for any scenario, the ventilation system could be designed such that the mining operation could be carried out safely and with minimum cost.

Seeking to enhance methane gas distribution forecast in terms of validity and reliability, different factors affecting this process were investigated in order to find the most significant ones. Since the gas content is among the most important parameters affecting the accurate assessment and prediction of the coal gas emission, the uncertainty-based estimation of gas content tends to end up with more reliable outcomes. As such, one should evaluate the uncertainty along with the methane gas emission estimation. The review of literature shows that despite valuable research, no work has been done to predict methane emission based on the gas content uncertainty. In fact, all models have assumed that the parameters affecting the methane emission level are certain, while these parameters are uncertain.

In this work, the gas content and its uncertainty in a coal mine are first measured using the geo-statistical modeling. Then four main factors are selected to predict methane gas emission, and an uncertainty model is constructed to predict and evaluate methane emission using the Monte Carlo simulation method. The outputs of the Monte Carlo simulations were introduced into CFD modeling to estimate methane distribution across the working face and formulate the mine ventilate system accordingly considering the uncertain nature of the gas content. This led to identification of EMZs, as the main objective of the present work, where hazardous accumulations of methane within explosive limit can establish. Delineation of EMZs contributes to a safe operation of the mine for the mining workers. Therefore, the present article demonstrates an attempt to present this method and methane distribution to help prevent and control gas-driven disasters, while improving the control level significantly.

3. Methodology

A smoothing impact is to be expected when utilizing the interpolated reserve models as the foundation for mine design. This is owing to the fact that spatial interpolators are often intended to reduce estimation errors. Conditional simulation approaches in geo-statistics, on the other hand, have been created to assess the variability and uncertainty associated with geology [34].

Figure 1 shows the process of the research method in the form of a flowchart. It highlights the relationship between the steps of the CFD model and the statistical approach developed to investigate the effects of uncertainty of the gas content parameters on the evaluation of gas concentration distribution. For determining the spatial distributions of the gas contents, a sequential Gaussian simulation (SGSIM) was conducted throughout the analyzed region. Realizations from conditional simulation is used as the input for the Monte Carlo simulation. The rest of the influential parameters are entered into the simulation process as constants. The Monte Carlo simulation is used to generate a list of random samples for independent analyses and a combination of input parameters and their effect on the output variable. The output of the Monte Carlo simulation is the prediction of the emitted methane. The results of the Monte Carlo simulations are used as input to the CFD simulations.

The CFD study was done to understand the 3D prediction of methane gas emission distribution under uncertainty in terms of gas content.

4. Model description

The model-based experiments were carried out in order to estimate the effect of uncertainty of gas content (UGC) on the distribution of methane concentration in the working face. CFD was used to do experiments on a spatial representation of the region under consideration. The real value block model, an estimated average-type block model using universal kriging, and 20 conditionally simulated realizations utilizing sequential Gaussian simulation.

4.1. Geo-statistical simulation

In this work, the in-place gas content and related uncertainty were assessed in a coal mine. The corresponding analysis improved the design, and resulted in the implementation of a methane capture and control system. We employed two approaches for this purpose: kriging and sequential Gaussian simulation, and the results were compared in terms of variance and distribution. When the ultimate goal function is to reduce a single prediction error or to construct a uniform exploration map of an unknown property, the kriging approach is advised. The simulation, on the other hand, is recommended for situations in which the primary goal is to appropriately evaluate confidence intervals or simulate some spatial continuity [35]. However, with the geo-statistical technique, there is no clear criterion for ruling out simulation or kriging [35]. The simulation methodology differs from the kriging technique in that it is capable of replicating the spatial continuity patterns and realistic uncertainty models. This distinction is due to the intrinsic preference of both techniques. As a result, SGSIM was chosen as the best analytical approach in this work.

The current work developed 20 realizations for the required characteristic of gas content using varying numbers of grids to guarantee that the data was random. These simulations were run to investigate the uncertainty and distributions of various characteristics over the research region.

Although both SGSIM and universal kriging were used in this work, the simulation surpasses kriging in respect of uncertainty assessment [35] (in the WINGSLIB software). The realization takes the form of a set of simulated maps that represent an uncertain map with the same probability. As a result, a grid depicts the distributions of specified qualities in each realization (i.e. simulated map). The data may then be statistically analyzed for variance and related uncertainty in the form of probability using this distribution.

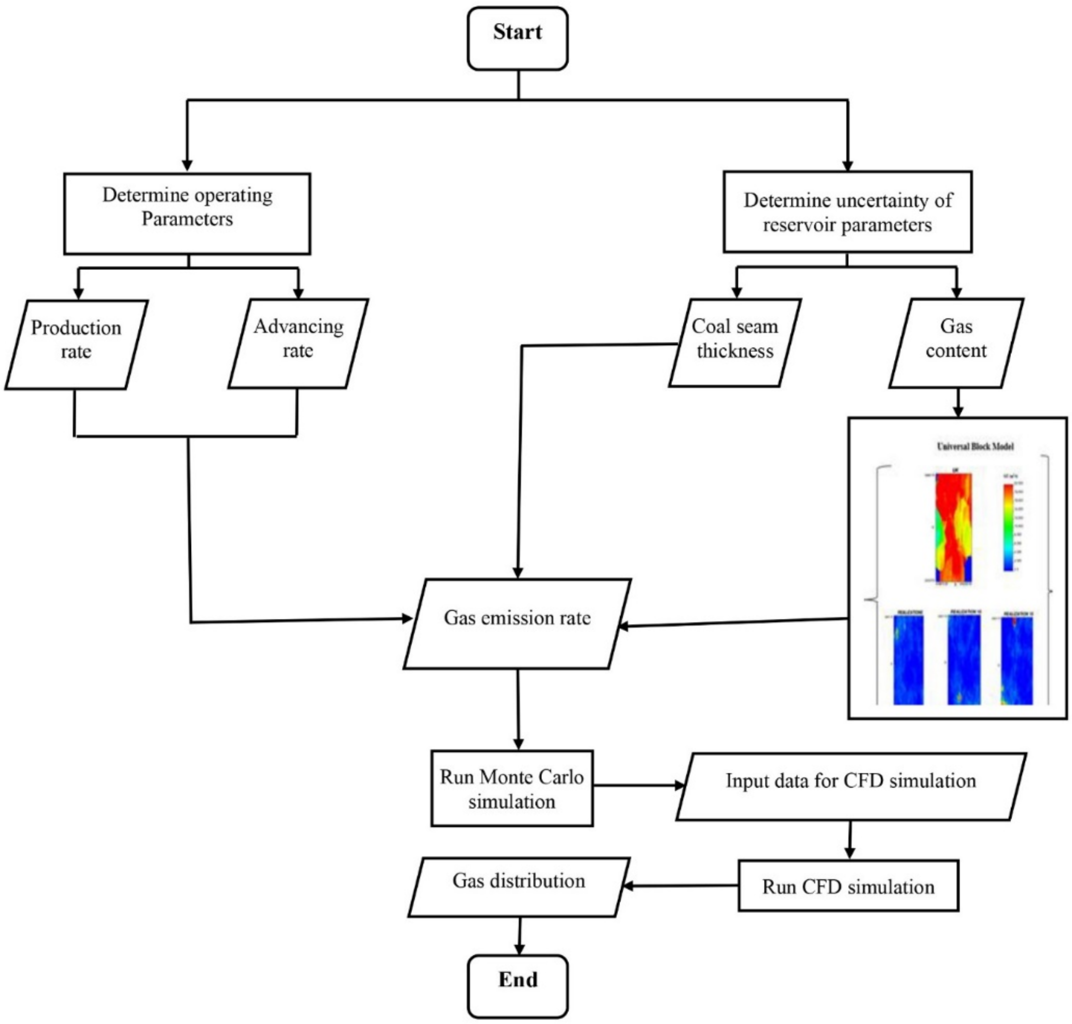


Figure 1. Flowchart of research method process.

4.2. Monte Carlo simulation

Monte Carlo simulation is one of the most efficient methods used to analyze complex problems as a computational algorithm [36]. The first step in performing the Monte Carlo simulation is to determine the distribution function for the random variables. The Monte Carlo simulation is mostly used to describe a method to reflect the uncertainties at the model input to uncertainties at the model output. Therefore, the Monte Carlo is a kind of simulation that explicitly and quantitatively shows the uncertainty. The Monte Carlo simulation relies on the process of explicit representation of uncertainty by designating the inputs as the probability distributions. If the inputs describing a system are uncertain, then the prediction of the ongoing performance is definitely uncertain. This means that the result of any analysis based on the inputs represented by probability distributions is itself a probability distribution. Many parameters are considered for the safety and disaster control in the mine. Assuming the probability distributions and distribution parameters related to random variables, the MCS simulation is first performed for a sample of 100 items. Then for each parameter, the corresponding probability distribution is selected. In the next step, a random value is obtained for each distribution, and by repeating this process, the most probable solution is obtained as a distribution with a minimum and maximum value. The gas content is a very important parameter for assessing the methane emission through coal seams before and after the mining operations. Therefore, the gas content of a coal seam is one of the important parameters that should be considered for the ventilation purposes. In this work, four important factors for predicting the methane gas were investigated: gas content (m^3/t), coal thickness (m), advance rate (m/d), and production rate (t/d). The gas content is uncertain or random variables that affect the air flow required in the face, and the methane emission is a dependent variable. The distribution function is obtained using the historical information based on experience or experiment. For gas content, a normal distribution function with a mean of 8.52 and standard deviation of 4.89 is assumed. Assuming the probability distribution and distribution parameters along with the random variables, the Monte Carlo simulation was first run 100 times. In order to obtain a good level of probability distribution, the number of Monte Carlo simulation samples should increase. In this work, the Monte Carlo simulations were run 1000 times. It is important to note here that only the gas content uncertainty obtained in the previous step (gas content enters the Monte Carlo simulation in the form of uncertainty) is considered on methane emission, and the other parameters are constant.

The characterices of parameters effective in predicting the gas emission are given in Table 1.

Table 1. Input data.

No.	Gas emission (m^3/min)	Gas content (m^3/t)	Coal thickness (m)	Advance rate (m/d)	Production (t/d)
1	7.58	6.95	2.5	3.4	725
2	7.44	7.37	2.6	3.6	727
3	8.51	7.59	2.1	3.5	789
4	8.51	7.84	2.5	3.8	768
5	8.42	7.36	2.3	3.5	637
6	8.16	7.62	2.5	4.2	769
7	8.58	7.94	1.9	3.7	692
1	7.58	6.95	2.5	3.4	725

4.3. Numerical simulation modeling

ANSYS Fluent 19.3, a CFD software, was used to run the simulations governed by a 3D elliptic fluid flow equation. The equation was solved for numerical results using segregated 3D double-precision solver that was processed through parallel computing. Assuming a 3D, steady, incompressible flow within the computational domain, the brattice and duct (and the adjacent zones) were modeled using grids of no smaller than 2.3 cm in size, while the near-surface zone was simulated by a maximum grid size of 10 cm. Various scenarios of flow were considered based on turbulent air flow under the k-ε turbulence model [18, 22]. Only the equations referring to the conservations of mass and momentum were solved as the heat transfer equations were beyond the scope of this work.

The governing equations were discretized by means of the SIMPLE algorithm via a finite-volume integral method, with the momentum conservation expression handled by second-order upwind discretization technique. Iterations were continued until the residual value fell below 10^{-5} and 10^{-4} for the momentum and turbulence equations, respectively, defining a convergence criterion. The specific parameters are:

- The air intake is of the dimensions 3 m × 4 m × 20 m.
- The air return is of the dimensions 3 m × 4 m × 20 m.
- The volume of the coal working face is 3 m × 4 m × 12 m.
- Length of brattice is 11 m and at 0.6 m to the cross-cut section.
- Diameter of ducted fan system is 0.8 m within 5 m of the working face

Figure 2 presents the geometry of the methane emission zone for the case study. It was a 2D model of an underground coal mine equipped with air inflow and outflow conduits to let the fresh air flow into the mine and blow the contaminated air out of the mine, respectively.

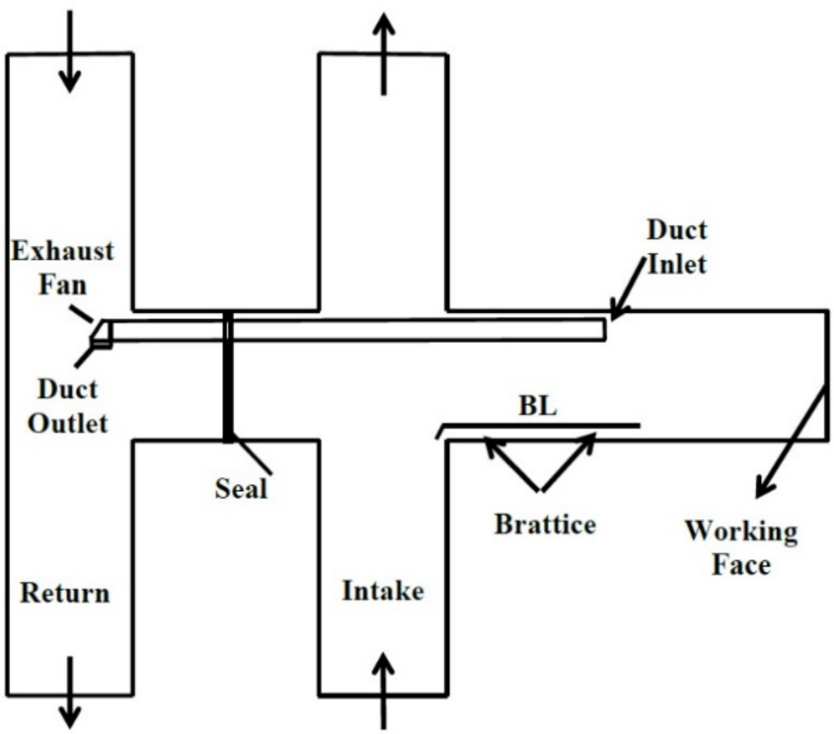


Figure 2. Computational model in top view.

a) *Boundary conditions*
- ✓ At walls: the standard wall function is used in all simulations
- ✓ Velocity inlet: 2 m/s
- ✓ Methane inlet: 0.06 m^3/s (Base case)
- ✓ Pressure outlet: 0 Pa.

5. Model validation

Several investigations in the literature have verified the numerical model against the *in-situ* experimental data. A prior research work by Hashimenasb *et al*. [32] has confirmed the numerical model with the experimental results of Parra *et al*. (2006). The results obtained revealed that there was a very strong agreement between the current model's results and the work of Parra *et al*. [20]. It is worth noting that the boundary condition for the base case was validated by Hasheminasab *et al*. [32], who assumed no change in gas content. To check for the effect of UGC on methane gas distribution concentration, one other scenario was developed with coupled Monte Carlo-Gaussian simulations (taken from MCS), and the validated CFD model was run under the same initial and operating conditions (Table 2).

Table 2. List of simulation scenarios.

Scenarios	Gas emission (m^3/s)
Base case	0.06
Effect of UGS	0.136

6. Result and Discussion

In this work, a combination of three simulation concepts, namely geo-statistical simulation to capture in-situ gas content uncertainty, and Monte Carlo simulation, was used to predict coal gas emission based on the *in-situ* gas content uncertainty. CFD simulation shows methane concertation and distribution. Accordingly, the proper ventilation can be planned for the mine.

The simulations made it possible to come up with lots of novel outcomes. The effect of UGC on methane gas distribution concentration in the development zone was given special attention. As mentioned earlier, no such testing had ever been conducted. Therefore, assessments were carried out for two scenarios: one is a base case model, while the other is a model that includes the effect of UGC on methane gas distribution. All the input geometrical, physical, and chemical parameters were the same in both situations in order to compare.

The resulting study indicate considerable disparities for both scenarios under evaluation. The study of the distributions obtained clearly shows that UGC has a significant impact on EMZs. This has a significant effect on the distribution of methane concentrations in this region, as shown in Figure 3(b). Figure 3 depicts the distributions observed for system with the effect of UGC and without it (base case). The effect of UGC at the working face affects the position of the maximum methane concentrations.

The figure further demonstrates that the dimensions of EMZ are directly related to the level of uncertainty associated with the gas content. According to the figure, an EMZ was identified in the upper left part of the mining face where methane was constantly leaking out of the face and the leftward flow of air in front part of the mining face tends to accumulate the emitted gas. Given this scheme, the place where an EMZ is established across the face is primarily controlled by the airflow characteristics, i.e. any mining activity that influences the air flow can potentially affect the gas distribution. The outcomes showed probable development of EMZ in the upper left part of the mining face (V = 2 m/s) and that one could attenuate or somewhat displace the gas accumulation out of the working face by increase in the air velocity, thereby providing for a safer mining work space.

According to Figure 4, the methane concentration with uncertainty was found to reach as high as 4.47% and base case was 2.16%. The figure further shows that the gas content is the key factor controlling the gas distribution across the mining face. Based on the results of the analysis, allowable gas concentration in the air mixture under actual condition was close to the explosive threshold, possibly due to the coal mining-induced gas emission into the mining space. Should a flow of air at a higher velocity be supplied to the working face, methane concentration can be maintained below the explosive threshold along the entire length of the wall.

Table 3 compares the methane concentration values obtained for the system with UGC and the base case at the working face.

Table 3. Comparing methane concentration.

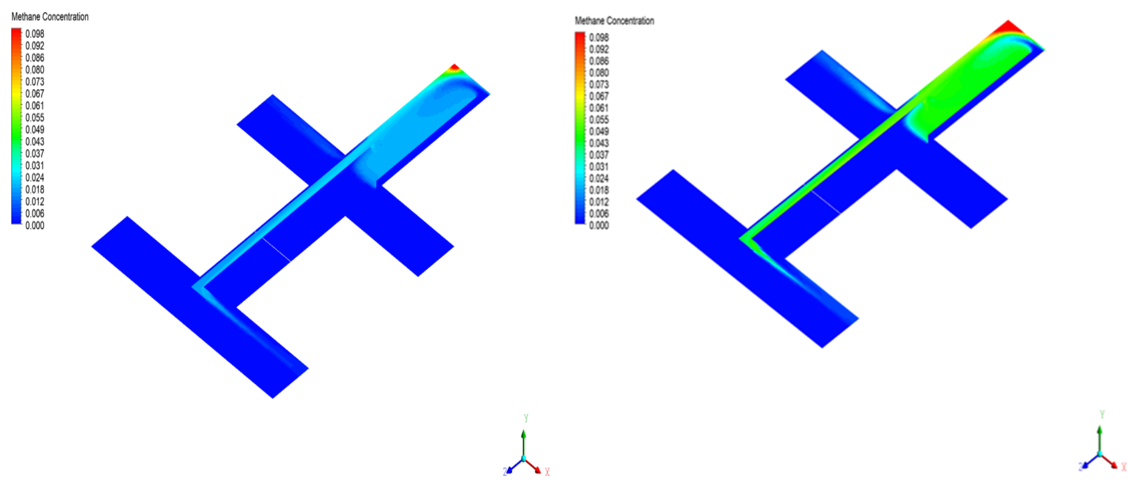
Scenarios	Methane concentration %
Base case	2.16
Effect of UGS	4.47

The base case model has much less concentration than the average of the 20 realizations (UGC). The based case model clearly underestimates methane gas concentration for the specified schedule. This is mostly owing to ignoring the *in-situ* variability and gas content uncertainty. The ability of conditional simulation to measure gas content uncertainty enhances the ventilation system performance prediction. It should be noted that the use of average-type estimated models (base case) does not always result in underestimate. These procedures may potentially result in an overestimation depending on local geological circumstances. The results show that utilizing uncertainty gas content to predict gas emissions is effective.

The average values for methane concentration levels were also calculated by the paper's authors. It was thought that presenting the results in this manner would offer a more complete explanation of the methane distributions and the effect of UGC on these distributions. Considering both scenarios, the maximum average methane concentration was 1.7%. On the other hand, the methane concentration base case was found

0.8%. After evaluating the distributions (Figures 3 and 4), it is clear that variability of gas content has a significant impact on the increase in the methane concentration levels in the working face.

In order to achieve a safe mining operation, one must consider EMZs wherein the gas concentration may exceed the explosive threshold. Moreover, a proper design of ventilation system can be achieved only based on a good knowledge of the gas emission rate and locality.



(a) (b)

Figure 3. EMZs in vicinity of mining face a) base case, b) with effect of UGC.

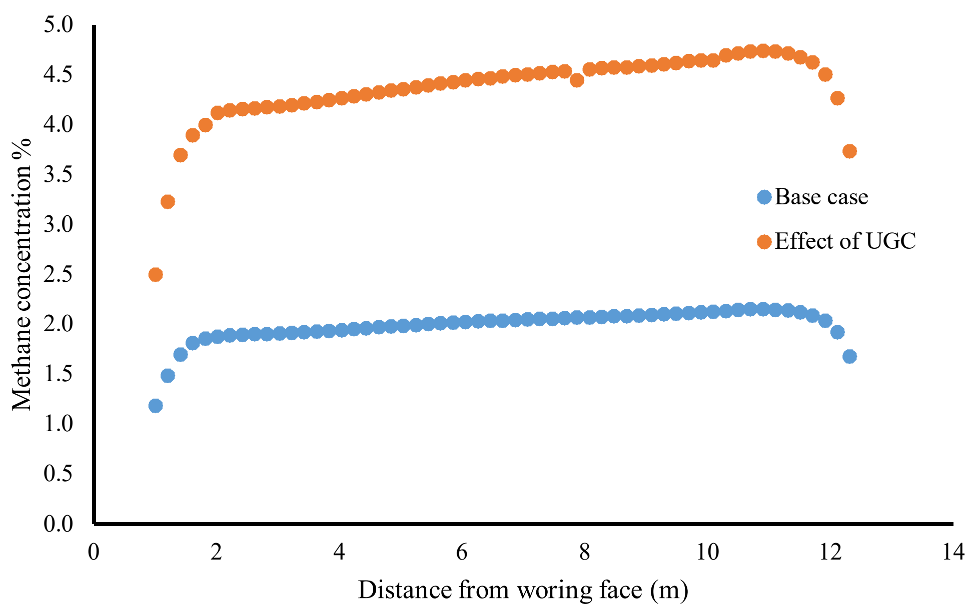


Figure 4. Methane gas concentrations percentage for both scenarios.

7. Conclusions

In mining, the methane gas concentrations above an allowable threshold are deemed highly hazardous due to their susceptibility to explosion. This highlights the remarkable importance of the research on the methane accumulation prevention. This can be done by estimating the gas distribution considering different uncertainties associated with mine-related excavations and identifying the factors determining such distribution.

The goal of the studies was to see how the uncertainty gas content affected the distribution and concentration of methane in an active extraction region.

It is necessary to understand the gas emission zones including the gas concentration and related uncertainties in order to properly manage methane gas in underground coal mines.

In this paper, the uncertainty associated with the gas emission and the factors affecting this uncertainty were investigated. Accordingly, gas emission was calculated based on the uncertain parameters such as gas content. The Monte Carlo simulation was utilized in order to estimate the gas emission and the impact of the uncertainty associated with the gas content on the gas emission, which was taken as input to the CFD simulation. To this end, various physical equations (e.g. equations of momentum, continuity, turbulence, fan, and gas diffusion) were solved utilizing CFD as implemented in the Ansys Fluent. Gas distribution was evaluated using CFD to forecast methane gas distribution across the working face.

The findings clearly show that UGC has an impact on the ventilation parameters and EMZs. Also the dimensions of the zone of elevated methane gas are directly changed by the variability gas content. With the UGC effect, methane concentration has increased, and EMZs have also expanded. However, the experimental results show it clearly that a combination of the three methodologies presented in this article can serve as an effective procedure for analyzing the ventilation performance and detect critical situations.

References

[1]. Zhang, Z.M. and Wu, Y. (2014). China coalmine gas-geologic laws and mapping, China University of mining and technology press.

[2]. Noack, N. (1998). Control of gas emissions in underground coal mines, International Journal of Coal geology 35, 57-81

[3]. Saghafi, A. (2017). Discussion on determination of gas content of coal and uncertainties of measurement. International Journal of Mining Science and Technology. 27 (5): 741-748. doi:10.1016/j.ijmst.2017.07.024.

[4]. Pope, J., Dutton, A., and Nelson, C. (2015). Uncertainty and variability in gas desorption measurements from coal.

[5]. Webster, R. and Oliver, M.A. (2009). Geostatistics for Environmental Scientists, 2nd edition. Wiley, West Sussex, England. 330 pp.

[6]. Hohn, M.E. and Neal, D.W. (1986). Geo-statistical analysis of gas potential in Devonian shales of West Virginia. Computers and Geosciences 12, 611–617.

[7]. Olea, R.A., Luppens, J.A., and Tewalt, S.J. (2011). Methodology for quantifying uncertainty in coal assessments with an application to a Texas lignite deposit. International Journal of Coal Geology. 85 (1): 78–90.

[8]. Leuangthong, O., Khan, KD., and Deutsch. (2008). CV:Solved Problems in Geostatistics, Wiley. Hoboken, New Jersey, 207 pp.

[9]. Karacan, C.Ö., Olea, R.A., and Goodman, G. (2012). Geostatistical modeling of the gas emission zone and its in-place gas content for Pittsburgh-seam mines using sequential Gaussian simulation.Int.J.CoalGeol. 90–91, 50–71.

[10]. Zhou, F., Allison, G., Wang, J., Sun, Q., Xiong, D., and Cinar, Y. (2012). Stochastic modeling of coalbed methane resources: a case Study in southeast Qinshui Basin, China. Int. J. Coal Geol. 99, 16–26.

[11]. Karacan, C. Ö. (2015). Analysis of gob gas venthole production performances for strata gas control in longwall mining. Int. J. Rock Mech. Min. 9e18.

[12]. Zhou., F. and Z., Guan. (2016). Uncertainty in estimation of coalbed methane resources by geological modelling. Journal of Natural Gas Science and Engineering 33: 988-1001.

[13]. Lei, L. (2014). Prediction of gas emission quantity using artificial neural networks. Journal of Chemical and Pharmaceutical Research. 6 (6): 1653-1657.

[14]. Zhou, F., Yao, G., and Tyson, S. (2015). Impact of geological modeling processes on spatial coalbed methane resource estimation. International Journal of Coal Geology. 146, 14-27.

[15] Heerden, J. and Sullivan, P. (1993). The application of CFD for evaluation of dust suppression and auxiliary ventilation systems used with continuous

miners, 6th US Mine Ventilation Symposium. Littleton, USA.

[16]. Srinivasa, R.B. (1993). Design and development of a multi-scrubber dust control system for longwall faces: experimental and modeling studies, PhD Thesis, University of Wollongong.

[17]. Edwards, J. S., *et al*. (1995). Using Computational Fluid Dynamics (CFD) to solve mine safety and health problems, APCOM XXV 1995 Conference. Brisbane, Australia.

[18]. Sasmito, A.P., Birgersson, E., Ly, H.C., and Mujumdar, A.S. (2013). Some approaches to improve ventilation system in underground coal mines environment–a computational fluid dynamic study. Tunn. Undergr. Space Technol. 34, 82–95.

[19]. Wala, M. A. *et al*., (1998). Evaluation of the face ventilation systems for extended cuts with remotely operated mining machines using three-dimensional numerical simulations, SME Annual Meeting. Orlando, USA.

[20]. Parra, M., Villafruela, J., Castro, F., and Mendez, C. (2006). Numerical and experimental analysis of different ventilation systems in deep mines. Build. Environ. 41 (2): 87–93.

[21]. Hargreaves, D.M. and Lowndes, I.S. (2007). The computational modeling of the ventilation flows within rapid development drivage. Tunneling and Underground Space Technology 22, 150 -160.

[22]. Aminosadati, S.M. and Hooman, K. (2008). Numerical simulation of ventilation air flow in underground mine workings. In: Proceeding of the 12th North American Mine Ventilation Symposium 2008, pp. 253–259.

[23]. Torano, J.A., Rodriguez, R., Diego, I., Rivas, J.M., and Pelegry, A. (2007). Influence of the pile

shape on wind erosion CFD emission simulation, Appl. Math. Model. 31 2007. 2487-2502.

[24]. Torno, S., Torano, J.A., Ulecia, M., and Allende, C. (2013). Conventional and numerical models of blasting gas behavior in auxiliary ventilation of mining headings, Tunneling and Underground Space Technology 34, 73-81.

[25]. Kenny, L. C. B. *et al*. (2012). A study of flow patterns in different mining configurations of a horseshoe mine tunnel, Singapore: Technical report: Report No. M3TC TN-12-03, National University of Singapore.

[26]. Balusu. R., *et al*. (2005). Longwall goaf gas drainage and control strategies for highly gassy mines, 8th international mine ventilation congress, Brisbane, Australia, 2005.

[27] Ren. T., *et al*. (1997). CFD modeling of methane flow around longwall coal faces, 6th International Mine Ventilation Congress, Pittsburgh, USA.

[28]. Worrall, D. M. (2012). Modeling gas flows in longwall coal mines using Computational Fluid Dynamics, Ph.D. Thesis, The Colorado School of Mines.

[29]. Zheng, Y. and Tien, J. C., (2009). Simulation of longwall face methane distribution, SME Annual Meeting, Colorado, USA.

[30]. Ren, T. and Wang, Z., (2013). Computational Fluid Dynamics modeling of respirable dust and gas behavior on a longwall face, The 2nd Australian Mine Ventilation Conference. Adelaide, Australia, 1-3 July.

[31]. Cheng, J., Li, S., Zhang, F., Zhoa, C., and Yang, SH. (2016). CFD modelling of ventilation optimization for improving mine safety in longwall working faces. Journal of Loss Prevention in the Process Industries, 40, 285-297.

[32]. Hasheminasab, F., Bagherpour, R., and Aminossadati, S.M. (2019). Numerical simulation of methane distribution in development zones of underground coal mines equipped with auxiliary ventilation. Tunneling and Underground Space Technology 89, 68-77.

[33]. Rahimi, S., Ataee-Pour, M., Madani, H., and Aminossadati, S.M. (2021). Investigating the impact of gas emission uncertainty on airflow distribution in an auxiliary ventilation system using CFD and Monte-Carlo simulation. Build. Environ., 204, 108165.

[34]. Chiles, J.P. and Delfiner, P. (2012). Geo-statistics: Modeling Spatial Uncertainty. 2nd Edn. Wiley, Hoboken, NJ.

[35]. Olea, R.A. (2009). A Practical Primer on Geostatistics. US. Department ofthe Interior. US Geological Survey, Open-File Report 2009-1103. 346 pp.

[36]. Cheng, J. (2016). Assessment of mine ventilation system reliability using random simulation method. Environmental Engineering and Management Journal. 15 (4): 841-850.

مدلسازی تاثیر عدم‌قطعیت گازخیزی بر توزیع گازمتان با استفاده از دینامیک سیالات محاسباتی در راهروی پیشروی معادن زغال‌سنگ زیرزمینی

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چکیده:

امروزه یکی از مسائل عمده درحوزه ایمنی معدنکاری زیرزمینی زغال سنگ، حضور گاز متان است. در فرایند طراحی تهویه معادن زغال‌سنگ، درک صحیح آهنگ انتشار گاز متان و توزیع غلظت آن درجبهه‌کار زغال‌سنگ عامل مهمی است. این امر همچنین مسئولین معدن را قادر می‌سازد تا تجمع گاز را در منطقه جبهه‌کار زغال‌سنگ بهتر مدیریت کنند. پیش‌بینی انتشار گاز مدت‌هاست با عدم‌قطعیت ناشی از پارامترهایی مانند میزان گازخیزی همراه است. از این رو در این مطالعه، عدم‌قطعیت گازخیزی در یک لایه زغال سنگ ابتدا با استفاده از شبیه‌سازی زمین آماری بررسی و سپس روشی برای پیش‌بینی انتشار گاز متان بر اساس روش شبیه‌سازی تصادفی مونت کارلو پیشنهاد می‌شود. نتایج به‌دست‌آمده بعنوان داده‌های ورودی در مدل دینامیک سیالات محاسباتی سه بعدی (CFD) برای تخمین توزیع متان با در نظر گرفتن عدم قطعیت مرتبط با گازخیزی مورد استفاده قرار گرفت. باید در سراسر جبهه‌کار مناطق تجمع گاز متان (EMZs) به عنوان مناطقی که احتمال وقوع انفجار بسیار بالا است، مشخص شوند. نتایج به‌دست‌آمده نشان می‌دهد که عدم‌قطعیت گازخیزی بر پارامترهای تهویه و ناحیه تجمع گازمتان تاثیرگذار است. روش پیشنهادی را می‌توان به عنوان یک پارامتر تاثیرگذار برای بهبود فرایند طراحی تهویه در راستای افزایش فاکتور ایمنی به‌کار برد.

کلمات کلیدی: دینامیک سیالات محاسباتی، انتشارگاز متان، عدم‌قطعیت گازخیزی، مونت کارلو، مناطق تجمع گاز متان(EMZs).