1-1-2015

Modelling of gas and ventilation flow characteristics at an underground in-seam drilling site

Ting Ren
University of Wollongong, tren@uow.edu.au

Zhongwei Wang
University of Wollongong, zhongwei@uow.edu.au

Yuanping Cheng
China University of Mining and Technology, yuanping@uow.edu.au

Jian Zhang
University of Wollongong, jz164@uowmail.edu.au

Frank Hungerford
University of Wollongong, fh745@uowmail.edu.au

Modelling of gas and ventilation flow characteristics at an underground in-seam drilling site

Abstract

Gas management has always been a challenging issue for mine operators, and this is becoming increasingly significant as the mining depth increases. Gas drainage sites or stubs are established to drill in-seam boreholes for pre-draining coal seam gas prior to gateroad development and longwall mining. The management of ventilation and gas emissions within the drainage site becomes a critical component of mine safety during gas drainage process. In this study, a three-dimensional (3D) computational fluid dynamics (CFD) model was developed based on an Australian in-seam drilling site to investigate the aerodynamics of seam gas (methane and carbon dioxide) emitting from the drilling site and boreholes during normal drilling, and in the case of a sudden gas inrush from the borehole. The model incorporates the major equipment within the drilling site and the common ventilation management practices (e.g., brattice and vent tube). Mesh independence studies were conducted to achieve a mesh independent solution. Initially, steady state calculations were conducted to analyze the effectiveness of different ventilation controls on gas removal, after which transient simulations were carried out to investigate the dynamic emission of gas from a borehole. Modeling results indicate that potential high risk zones can be formed if sufficient ventilation cannot be provided to the drainage site, particularly during a high gas inrush event from a borehole. The treatment of borehole discharges, the configuration of brattice as well as the layout of ventilation tubes all played important role in effective gas management. This study has demonstrated that CFD modeling technique can be a useful tool for the design of optimum ventilation/ gas management in underground gas drainage site in coal mines, especially when abnormal gas emission is encountered during drainage operations.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Ren, T., Wang, Z., Cheng, Y., Zhang, J. & Hungerford, F. (2015). Modelling of gas and ventilation flow characteristics at an underground in-seam drilling site. Proceedings of 32nd Annual International Pittsburgh Coal Conference Omnipress.

Modelling of gas and ventilation flow characteristics at an underground in-seam drilling site

Ting Ren[a], Zhongwei Wang[a], Yuanping Cheng[b], Jian Zhang[a], Frank Hungerford[a,c],

[a]*Centre of Infrastructure Protection and Mining Safety, Faculty of Engineering and Information Sciences, University of Wollongong, NSW, 2522, Australia*
[b]*School of Safety Engineering, China University of Mining and Technology, Xuzhou, 221116, China*
[c]*Valley Longwall International Pty Ltd, 8 Balook Drive, Beresfield, NSW, 2322, Australia*

Gas management has always been a challenging issue for mine operators, and this is becoming increasingly significant as the mining depth increases. Gas drainage sites or stubs are established to drill in-seam boreholes for pre-draining coal seam gas prior to gateroad development and longwall mining. The management of ventilation and gas emissions within the drainage site becomes a critical component of mine safety during gas drainage process. In this study, a three-dimensional (3D) computational fluid dynamics (CFD) model was developed based on an Australian in-seam drilling site to investigate the aerodynamics of seam gas (methane and carbon dioxide) emitting from the drilling site and boreholes during normal drilling, and in the case of a sudden gas inrush from the borehole. The model incorporates the major equipment within the drilling site and the common ventilation management practices (e.g., brattice and vent tube). Mesh independence studies were conducted to achieve a mesh independent solution. Initially, steady state calculations were conducted to analyze the effectiveness of different ventilation controls on gas removal, after which transient simulations were carried out to investigate the dynamic emission of gas from a borehole. Modeling results indicate that potential high risk zones can be formed if sufficient ventilation cannot be provided to the drainage site, particularly during a high gas inrush event from a borehole. The treatment of borehole discharges, the configuration of brattice as well as the layout of ventilation tubes all played important role in effective gas management. This study has demonstrated that CFD modeling technique can be a useful tool for the design of optimum ventilation/gas management in underground gas drainage site in coal mines, especially when abnormal gas emission is encountered during drainage operations.

Keywords: Computational Fluid Dynamics (CFD) modeling; drilling site; ventilation management; gas flow.

1. Introduction

Gas is commonly encountered in underground coal mining, and it has always been a major safety concern for mining operations. Historically, there are many mining tragedies caused by gas explosions which had taken away thousands of miners' lives. Even in the modern times, gas explosions occur from time to time throughout the world mining industry, not only in developing countries, but also in developed countries. Table 1 summarizes several serious mine disasters due to the occurrence of gas explosions in recent years [after 1]. Theses alarming fatalities indicate that more efforts are necessary to be made for better gas management in underground coal mines.

Mining professionals have always been seeking for effective approaches to control the gas emitted into underground working environment. Ventilation is undoubtedly the most efficient method to control the emission of gas; however, its effect on the gas dilution can vary significantly depending on specific ventilation configurations, i.e., the employment of air door, air regulator, brattice and vent tube, etc. at different locations in the ventilation system.

It is worth noting that trying to optimize ventilation system by changing ventilation configurations on site can be risky under the harsh underground condition, in particular when hazardous gas is a main safety concern. Therefore, it becomes increasingly significant to estimate the potential impact of different ventilation controls on gas movement behavior before conducting field ventilation adjustment. Currently, computational models have gained its popularity in mining research owing to its prominent advantages in terms of safety and low cost in operation.

Table 1. Major coal mine explosion incidents in recent years [after 1].

Country	Date	Coal Mine	Fatalities
China	14/02/2005	Sunjiawan, Haizhou shaft, Fuxin	214
USA	2/06/2006	Sago, West Virginia	12
Kazakhstan	20/09/2006	Lenina, Karaganda	43
Russia	19/03/2007	Ulyanovskaya, Kemerovo	108
Ukraine	19/11/2007	Zasyadko, Donetzk	101
USA	5/04/2010	Upper Big Branch, West Virginia,	29
Turkey	17/05/2010	Karadon, Zonguldak	30
New Zealand	19/11/2010	Pike River Mine	29
Turkey	13/05/2014	Soma, Turkey	301
Ukraine	4/03/2015	Zasyadko, Donetzk	33

The use of computational fluid dynamics (CFD) modeling technique in mining started at early 1990s,

Corresponding author's email: zhongwei@uow.edu.au

when Heerden and Sullivan [2] first investigated the ventilation and gas flow patterns in a development heading. At the same time, Srinivasa [3] modeled the air velocities distributions in a longwall face using a three dimensional CFD code. Later, a general process of conducting a CFD simulation was discussed by Edwards, et al. [4] by modeling the ventilation flow patterns within a heading, they also claimed that there was great potential for using CFD models to solve mine safety and health related problems. Then, the ventilation and gas flow at headings/drivages were modeled by many scholars, including Oberholzer and Meyer [5,6], Moloney and his colleagues [7,8], Wala, et al. [9], Parra, et al. [10], Hargreaves and Lowndes [11], Aminossadati and Hooman [12], Toraño, et al. [13,14], Kenny, et al. [15] and Sasmito, et al. [16]. Meanwhile, longwall goaf gas flow characteristics were investigated by Ren, et al. [17], Balusu, et al. [18] and Worrall [19] using CFD modeling approach. Regarding the modeling of ventilation and gas flow at longwall face, Zheng and Tien [20] simulated the methane flow behavior on a longwall face considering the methane emission from various contributors, i.e., methane emitted from the coal broken by the shearer, the coal on the face conveyor, coal ribs and coal on the belt. More recently, Ren and Wang [21] developed full scale 3D longwall models, which incorporated major longwall equipment, to further investigate the ventilation/gas/dust flow characteristics taken into account the impact of shearer position and cutting sequence.

Nowadays, with the mining depth increases, coal seams are becoming gassier, and gas drainage sites/stubs have constituted indispensable components of underground working zones in some gassy mines where extensive boreholes are implemented for the pre-drainage of coal seam gas. However, from above CFD modeling studies, it is noticed that majority of these studies are focused on the ventilation and gas management at development headings, and some of them on longwall face, meanwhile, the impact of time on gas migration is ignored in most studies, except Torno, et al. [14] who developed the so called 4D CFD models to determine the time required to sufficiently dilute the hazardous gases for a safe working environment at headings. To fill this gap, this study investigated the ventilation and gas flow characteristics within a typical underground drilling site under different ventilation controls and gas emission conditions, transient models were also employed to probe into the gas movement behavior taken into account the effect of time.

2. Development of computational model

A typical underground drilling site of an Australian mine is shown in Fig. 1. It can be seen that four major equipment were located within the drilling site, including the drilling rig, rod trailer, rod racks and fines bin. Brattice is generally used to assist the ventilation in the drainage site, and vent tube is also proposed under certain circumstances to enhance the ventilation through the site.

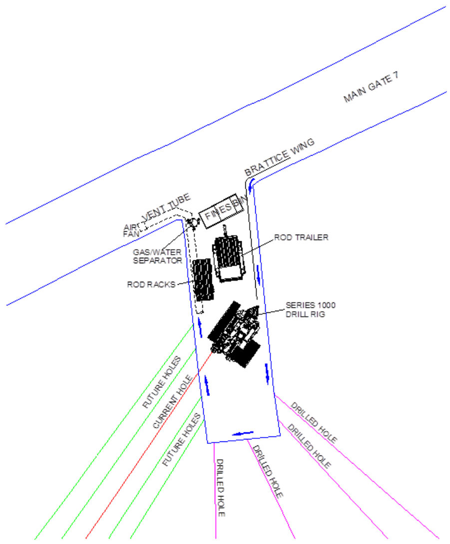


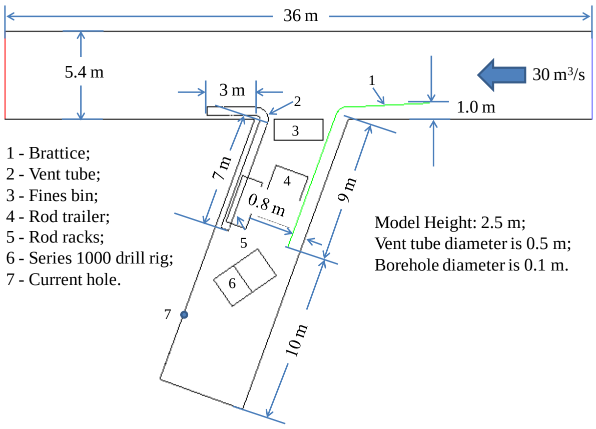
Fig. 1. A typical underground drilling site.

Based on above information, a 3D computational model was constructed incorporating simplified equipment profiles as well as the brattice and vent tube. An overview of the computational model is depicted in Fig. 2 where the model geometry, the position of equipment and main boundary conditions can be seen. Upon completion of the physical model, the model was meshed using tetrahedral method to accommodate its complex geometry. It is noticed that two meshing schemes were adopted to investigate the mesh independence of the model results. This was achieved by applying different sizing functions to edges, faces and volumes of the model, i.e. medium size controls were used in one meshing scheme which is denoted as medium mesh (1.05 million computational cells), and fine size controls were used in the other meshing scheme which is denoted as fine mesh (1.95 million computational cells) in the following sections.

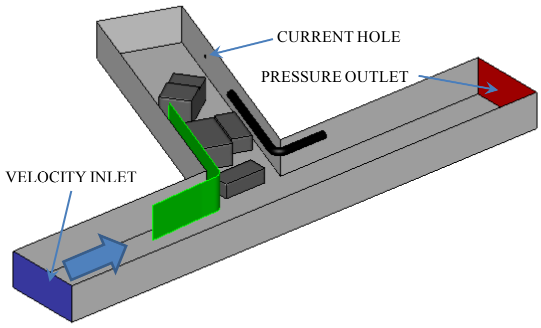
As indicated in Fig. 2b, boundary conditions of the model primarily involve the velocity inlet at the entry of domain and pressure outlet at the exit of the computational domain. Wall and fan boundary conditions are used to simulate the use of brattice and vent tube respectively; while interior boundary condition is used for them when there is no brattice and vent tube. For the other boundaries of the model, like the floor, roof, ribs and equipment surface, standard wall functions are adopted.

3. Mesh independence study

The numerical solutions of flow field rely greatly on the meshes used, and the solution asymptotically approaches to the exact solution as the mesh becomes finer. However, it does not necessarily mean the denser the mesh, the better the result will be. The discretisation error decreases as further refinement of the mesh however in the meantime the round off error increases. Therefore, it is beneficial to carry out the mesh independent study so as to ensure that both the discretisation and round-off errors are within acceptable level and the solution does not vary significantly with the mesh adopted. As mentioned in Section 2, both a medium mesh and a fine mesh were employed in this study to demonstrate the mesh independence of the solution.



(a) Plan view of the computational model



(b) 3D view of the computational model

Fig. 2. Overview of the computational model.

The case selected for mesh independence study is when only brattice is used to assist the ventilation to the drilling site, and the flow rate provided to the computational domain is 30 m^3/s. Mesh independences are investigated considering different flow features at different locations across the domain. Overall comparisons have been conducted by visualizing velocity contours and vectors at different cross sections from the simulation results of the two models, in which similar flow patterns have been observed. Meanwhile, two investigation lines were employed to examine the variation of velocity distribution along the two lines as indicated in Fig. 3. Fig. 4 and Fig. 5 respectively show the velocity profiles along the two investigation lines. It is apparent by comparing the profiles obtained from the two models results that the velocity distribution is not varying significantly with further refinement of the mesh, indicating a mesh independent solution has been achieved using the medium mesh. Consequently, results of the medium mesh have been used as base model in the following sections for flow field analysis and the gas flow behavior investigation.

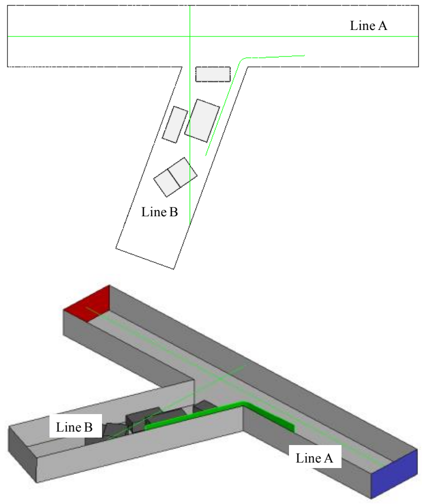


Fig. 3. Distribution of investigation line (Top: plan view; bottom: 3D view)

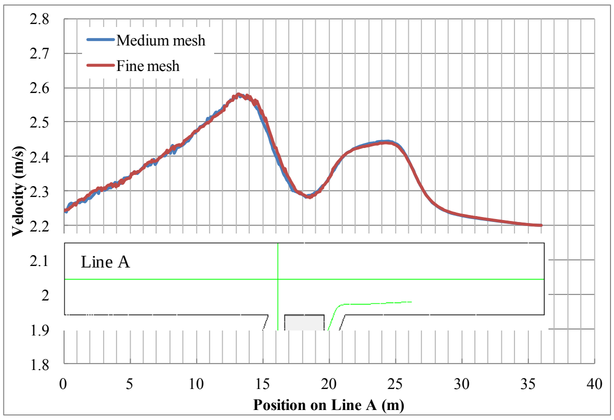


Fig. 4 Velocity variations on line A.

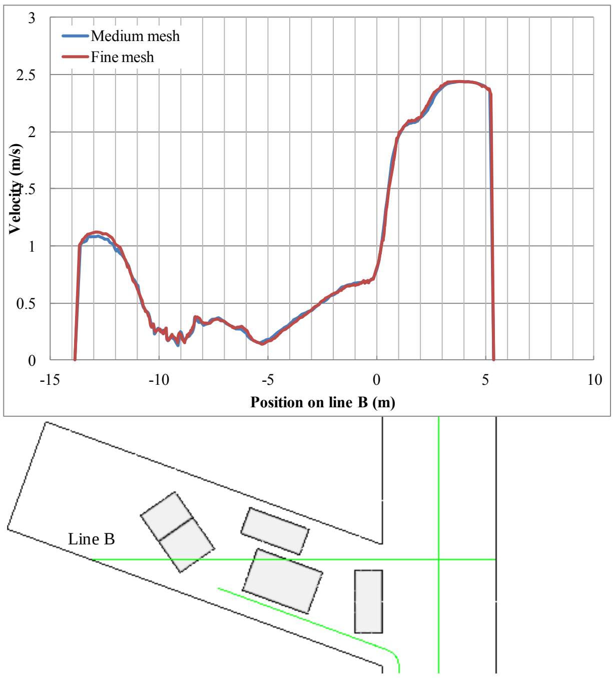


Fig. 5. Velocity variations on line B.

4. Model results and discussions

4.1 Gas flow characteristics

The distribution of methane gas in the drainage site was investigated by releasing methane from the three ribs of drilling site and the borehole (as indicated in Fig. 6a). The gas concentration distribution around the drilling site is shown in Fig. 6, where the impact of different ventilation management practices (e.g., brattice and vent tube) on the gas flow can be observed. As can be seen from Fig. 6a, it is apparent that if no ventilation controls were available on site to direct airflow into the drilling site, there would be significant amount of gas accumulating in the dead end zone, which is absolutely not suitable for workforces to work as well as the use of electrical equipment. As a common ventilation management practice, brattice is generally used in a variety of locations for the direction of airflow to desired zones. It can be seen from Fig. 6b that, with the use of brattice to assist the ventilation, there have been significant dilution of methane gas in the drainage site compared with the results of Fig. 6a where natural ventilation is adopted. The result of Fig. 6c indicates that the use of vent tube seems to be not as efficient as brattice in terms of diluting gas in the drainage site. This might be simply because the gas is emitted from the entire ribs, and the effective ventilation cross section of the vent tube is much smaller than that of the brattice formed, though the velocity is higher in the tube. And the suction of vent tube is limited to some extent in dealing with gas emitted from relatively large zones. Therefore, the use of vent tube alone with the configurations indicated in the model is not suggested for the gas dilution at the drilling site. Similar as exhaust ventilation for development headings, the performance of vent tube can be improved by further extension of the tube end to the face. Fig. 6d depicts the effect of combined use of brattice and vent tube. It seems that the combination of these two controls produces similar methane dilution effect as that of using brattice only, except slightly variation of the high gas concentration zones distribution at the entry of the drilling site. A 3D view of the gas concentration distribution under the two controls is shown in Fig. 7. It can be observed that with the assistance of vent tube, the high concentration of methane flows towards the suction tube rather than flows towards the roof, indicating the vent tube is helpful in dealing with the high concentration of gas emitted from the borehole.

In an open space, the gas distribution patterns rely heavily on the airflow patterns when the gas sources and compositions are known. Therefore, it would be easier to understand the gas distribution patterns depicted in Fig. 6 if the airflow patterns were well understood. Fig. 8 shows the air flow patterns in the drilling site with the use of brattice, vent tube, and a combination of these two controls respectively. It can be seen from Fig. 8a that certain amount of fresh air can be directed to the end of the drilling site which is good for the dilution of methane gas, though some small scales of circulation are generated. With the use of vent tube, airflow is sucked into the stub on the same side of vent tube (where the gas is better diluted), and the flow direction is therefore opposite to that shown in Fig. 8a where brattice is used. It is also noted that the overall velocity is lower than the velocity induced by brattice, resulting in relatively higher gas concentration in the drilling site as illustrated in Fig. 6c. When both brattice and vent tube are used, similar airflow patterns as that of using brattice is observed. Flow velocity is enhanced at the end of stub while flow is weakened in zones between brattice and vent tube where the gas gradually accumulates.

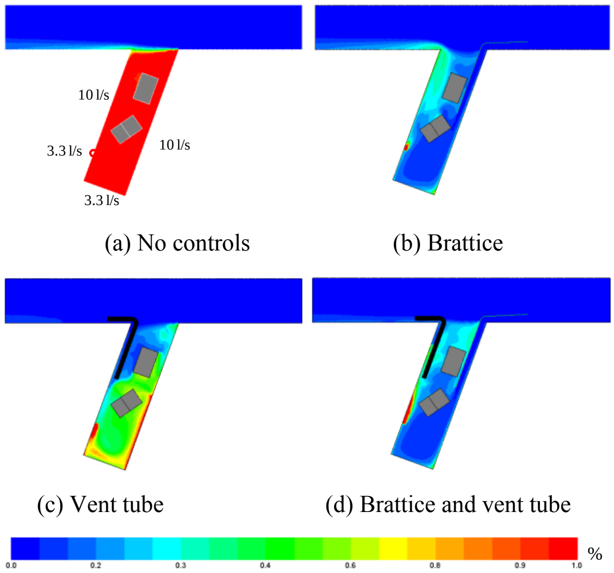


Fig. 6 Gas distribution under different ventilation controls (at borehole level, 1.2 m above floor).

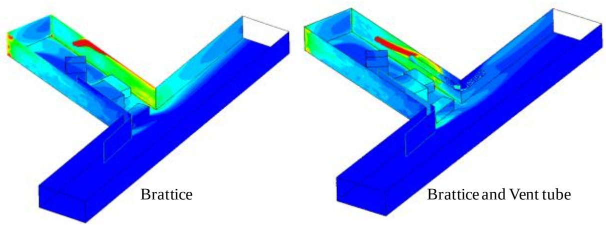
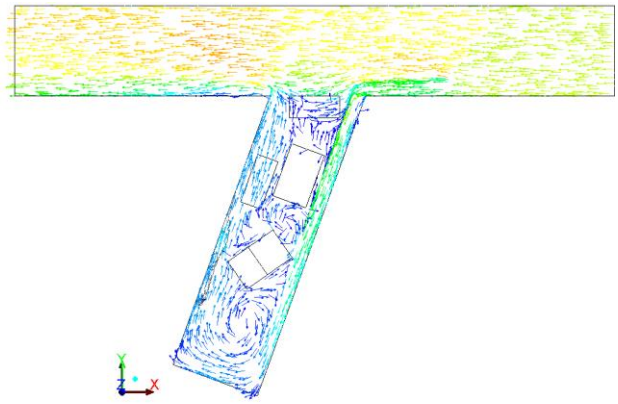


Fig. 7. 3D view of gas distribution inside the drilling site.

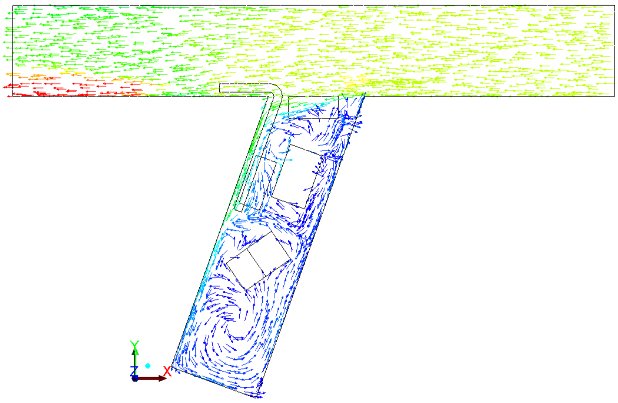
4.2 The occurrence of gas inrush

Field drilling practice demonstrates that gas inrush from borehole occurs under certain circumstances, especially when *in-situ* gas pressure is high. The occurrence of gas inrush event is critical to the safety of drillers working in the drainage site, it is therefore important to investigate the gas flow dynamics under such situations and evaluate the ventilation systems to ensure a safe working environment is provided.

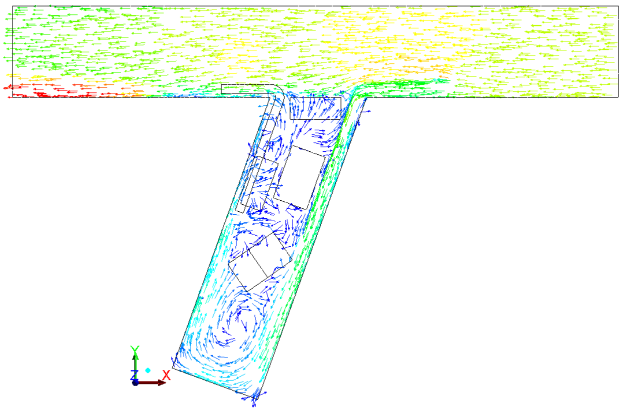
To investigate the behavior of dynamic gas emission from a borehole, transient calculations were conducted based on the previous steady model which used brattice as the ventilation control strategy. The sudden inrush of gas from a borehole was determined by the velocity from the borehole which decayed with time and was assumed to follow an exponent law as indicated in Fig. 9. Considering the initial emission velocity, two cases with an initial velocity of 2 m/s and 5 m/s were modeled and denoted as Case 1 and Case 2 respectively in the following section. Based on Case 2, another case was modeled which employed vent tube and is denoted as Case 3. A total of 10 seconds after the occurrence of gas inrush was modeled.



(a) Brattice



(b) Vent tube



(c) Brattice and vent tube

Fig. 8. Air flow patterns under different ventilation controls.

Figs. 10 to 12 respectively show the evolution of 1% iso-surface of gas concentration in the three cases. It can be seen that the inrush intensity and adoption of ventilation controls have significant impacts on the evolution of gas rich zone. Using brattice alone would be able to cope with a gas inrush event with relatively low intensity (i.e., an initial velocity of 2 m/s); however, when the inrush intensity is increased to an initial velocity of 5 m/s, the high concentration of gas would be able to migrate quickly to the top of the drill rig and it would also take longer to discharge the gas into the main gate. The impact of vent tube on discharging the excessive gas is clearly shown in Fig. 12, which demonstrates its effectiveness on dealing with a sudden gas inrush event, and the use of vent tube in combination with brattice is therefore suggested when there is potential of intense gas inrush from borehole.

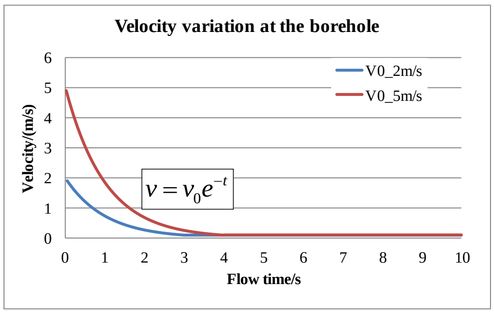


Fig. 9. Decay of gas inrush velocity at the borehole.

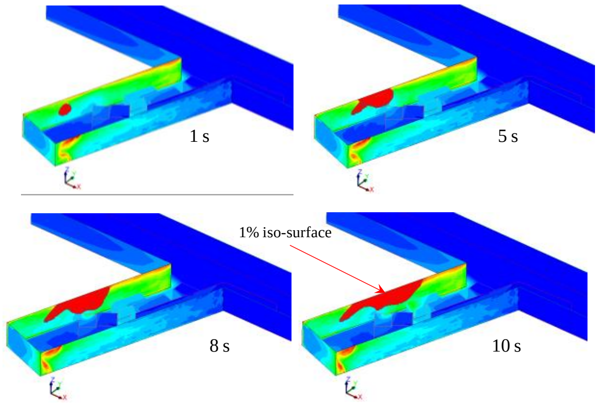


Fig. 10. The evolution of gas distribution in Case 1.

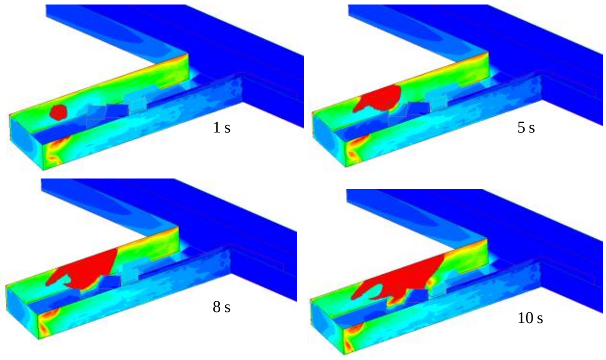


Fig. 11. The evolution of gas distribution in Case 2.

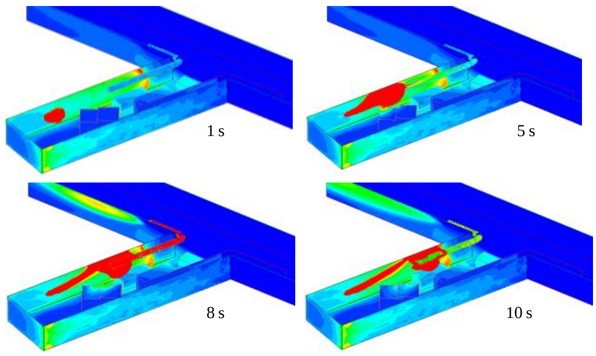


Fig. 12. The evolution of gas distribution in Case 3.

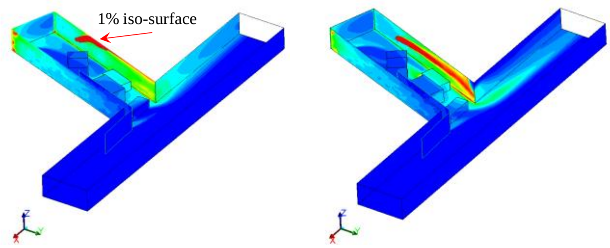
4.3 The impact of gas composition

In most circumstances, the gas emitted from coal seam is composed of several different kinds of gases. In Australian underground coal mines, methane and carbon dioxide are the most common components of coal seam gas. In some areas, methane is the dominant gas which may account for up to 90% of gas content, while in other areas more than 90% of gas may be carbon dioxide.

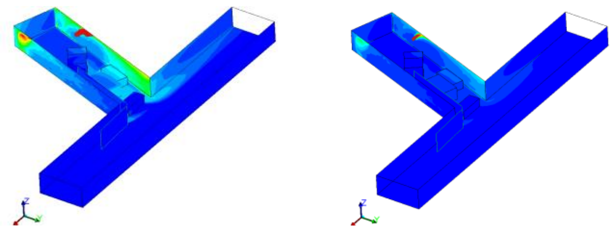
To investigate the flow behavior of gases emitted with different compositions, five cases as indicated in Table 2 were simulated and the modeled results are illustrated in Fig. 13. It is noted that brattice was used in the model. It can be seen from Fig. 13 that there have been significant difference in gas distribution as the gas components change. When the gas is pure methane, it tends to flow towards roof level which can also be observed in the transient model results depicted in Figs. 10 and 11; whereas when the gas is pure carbon dioxide, it is likely to disperse along the floor level. This kind of behavior lies in the density difference or the molecular mass difference of the emitted gas with that of air, that is the lighter gas will show a trend of gradually migrating upwards while the denser downwards. It is worth noting that the airflow also affects the gas flow behavior. As can be seen from Fig. 13a and 13b, due to the relatively high velocity at lower level (equipment occupies space), the downward migration of carbon dioxide is not as obvious as the upward migration of methane. The gas distribution pattern in the other three cases, in which both methane and carbon dioxide were released, varies between the previous two models results with pure methane and pure carbon dioxide emission. It is also noted from the model results that, when a mixture of methane and carbon dioxide is emitted, methane (carbon dioxide) behaves similarly to carbon dioxide (methane), and it seems like they are bonded together rather than behaving as individual gas migrating upwards or downwards. They share the same distribution patterns and only the concentration of the two gases varies from one another.

Table 2. Gas compositions used in the model.

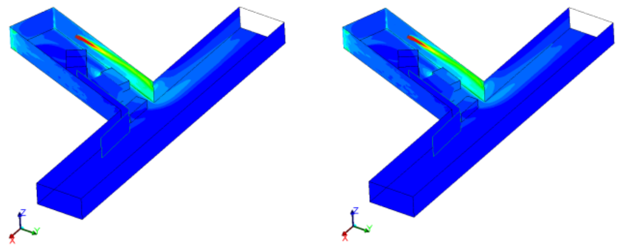
Model name	Gas composition	
	CH_4 (%)	CO_2 (%)
GC_1	100	0
GC_2	0	100
GC_3	70	30
GC_4	50	50
GC_5	30	70



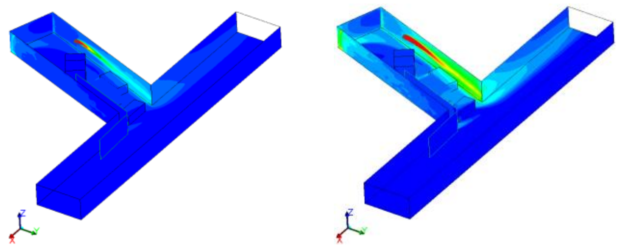
(a) CH_4 in GC_1 (b) CO_2 in GC_2



(c) CH_4 in GC_3 (d) CO_2 in GC_3



(e) CH_4 in GC_4 (f) CO_2 in GC_4



(g) CH_4 in GC_5 (h) CO_2 in GC_5

Fig. 13. Gas distribution with varying gas composition.

It is noted that the behavior of gas with varying components obtained from the model results has not been verified, and it would be desirable in the future to conduct field or lab tests to further verify this sort of mixed gas flow behavior.

5. Conclusions

3D CFD studies were conducted to understand the flow behavior of gas emitted into an underground in-seam drilling site. Both steady and transient calculations were carried out to mimic the process of normal drilling and the occurrence of a sudden gas inrush event. The performance of common ventilation management practices was also evaluated using the steady state models, where the importance of ventilation configurations in effective gas removal was demonstrated. In addition, the flow behavior of different gases was investigated by considering the composition of gas emitted into the drilling site.

Specifically, the model results obtained from this study can be summarized as follows:

- Significant amount of gas would accumulate in the drilling site if no ventilation controls are available on site which should be avoided all the time;

- The use of brattice is able to direct certain amount of fresh air to the drilling site which is demonstrated to be effective in diluting gas;
- The effect of vent tube in gas removal is limited without the assistance of brattice;
- The effect of gas dilution on the drainage site can be further enhanced by a combined use of brattice and vent tube;
- In the case of sudden gas inrush, using brattice alone would only be capable of dealing with an inrush event associated with low intensity;
- For gas inrush events with high intensity, both brattice and vent tube should be employed to efficiently discharge the excessive amount of gas emitted;
- Besides ventilation, the molecular mass of emitted gas also affects its flow behavior, i.e., the lighter gas has a potential to migrate upwards while the denser gas is likely to migrate downwards;
- When gas is emitted into the drilling site as a mixture of methane and carbon dioxide, both gases behave similarly as a whole and share the same distribution patterns.

References

[1] C. Ö. Karacan et al., Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction, International Journal of Coal Geology 86 (2011) 121-156.

[2] J. Heerden and P. Sullivan, The application of CFD for evaluation of dust suppression and auxiliary ventilation systems used with continuous miners, 6th US Mine Ventilation Symposium. Littleton, USA, 1993.

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

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

[5] D. R. J. W. Oberholzer and C. F. Meyer, The evaluation of heading ventilation systems through the use of computer simulations, 7th US Mine Ventilation Symposium. Lexington, USA, 1995a.

[6] D. R. J. W. Oberholzer and C. F. Meyer, Computer modeling in the solution of continuous miner heading ventilation problems, APCOM XXV 1995 Conference. Brisbane, Australia, 1995b.

[7] K. W. Moloney, An analysis of airflow patterns in auxiliary ventilated drivages, Ph.D. Thesis, University of Nottingham, 1997.

[8] K. W. Moloney and I. S. Lowndes, Comparison of measured underground air velocities and air flows simulated by Computational Fluid Dynamics, Trans. Inst. Min. Metall. (Sec. A: Min. Ind.), 108 (1999) 105-114.

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

[10] M. T. Parra et al., Numerical and experimental analysis of different ventilation systems in deep mines, Building and Environmental 41 (2006) 87-93.

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

[12] S. M. Aminosadati and K. Hooman, Numerical simulation of ventilation air flow in underground mine workings, 12th North American Mine Ventilation Symposium. Sparks, Nevada, USA, 2008.

[13] J. Toraño et al., Models of methane behavior in auxiliary ventilation of underground coal mining, International Journal of Coal Geology 80 (2009) 35-43.

[14] S. Torno et al., Conventional and numerical models of blasting gas behavior in auxiliary ventilation of mining headings, Tunneling and Underground Space Technology, 34 (2013) 73-81.

[15] L. C. B. Kenny et al., 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, 2012.

[16] A. P. Sasmito et al., Some approaches to improve ventilation system in underground coal mines environment – A computational fluid dynamic study, Tunneling and Underground Space Technology, 34 (2013) 82-95.

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

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

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

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

[21] T. Ren and Z. Wang, 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, 2013.