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GOAF GAS FLOW MODELLING IN 6KM LONG LONGWALL PANEL

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Abstract: Understanding the goaf gas distribution in the start-up areas and in 6km long retreat panel is critical for developing gas management and spontaneous combustion (sponcom) control strategies. Extensive computational fluid dynamics modelling studies have been conducted and calibrated using operational longwall goaf data to obtain fundamental understanding of the goaf gas flow patterns in 6km panel of various goaf lengths and the effect of goaf gas emission rates on the gas flow patterns were investigated. The paper presents the results of various numerical investigations in the 6km long panel for different goaf lengths of 500m, 1km, 3km and 6km under modelled field site conditions.

Keywords: Maingate (MG); Tailgate (TG); Goaf; Oxygen; Ingress;

1 INTRODUCTION

In order to achieve high production rates safely and improve mining economics, mine operators nowadays are increasing longwall panel lengths up to 6km and beyond. In highly gassy mining conditions and in coal seams prone to spontaneous combustion (sponcom), management of these two key issues is critical for successful operation of longwalls, particularly in longer panels. This research project builds on the previous research work and field studies carried out in the standard longwall panels under different mining conditions (Balusu et al., 2002a and 2004; Belle, 2015). As the panel layouts, gas emissions, ventilation systems, and dimensions of the new generation longwall panels are significantly different from the previous longwall panels, this collaborative research project has been undertaken to conduct detailed computational fluid dynamics (CFD) modelling studies to assist in the development of optimum sponcom management strategies for long longwall panels under highly gassy field site mining conditions. The requirement of high goaf gas drainage capacity due to highly gassy mining conditions and the need to prevent oxygen ingress into the goaf to minimize sponcom risk are contradictory to one another and should be considered during design and implementation of sponcom management systems.

Numerical studies using CFD techniques were carried out in the past few years for understanding the working environment of underground longwall face. Aziz et al., (1993) used numerical techniques to understand the ventilation mechanisms, gas and

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dust distributions in longwall mines. Balusu et al. (2001, 2002b, 2004) carried numerical and field data investigations on goaf gas flow mechanisms and proactive inertisation strategies for prevention of spontaneous combustion in gassy coal mines and developed various gas drainage strategies in underground longwall mines. Roy et al. (2010) investigated various gas management options for reduced greenhouse gas emissions. Yarlagadda et al. (2011) investigated various strategies for preventing sponcom in non-gassy coal mines extracting coal with the blasting gallery method. Tanguturi et al. (2013, 2014, 2015) carried investigations on goaf gas distribution and the methane gas migration near the TG region in gassy coal mine and studied various options for controlling the methane gas percentage near the TG region by controlling the ventilation flow.

In this paper, the CFD techniques were used to investigate the goaf gas distribution during various stages, i.e. 500m, 1km, 3km and 6km of longwall panel extraction. The main focus of the project during the initial phases was to obtain a fundamental understanding of goaf gas flow patterns in longwall panels under field site conditions using CFD modelling techniques. Based on the results of these investigations, appropriate strategies and guidelines have been developed for gas and sponcom management in the longwall panels under field site conditions.

2 CFD MODEL DEVELOPMENT

CFD models have been developed with different panel geometries of 500 m, 1km, 3km and 6km long goaf lengths of the longwall panel. Models have been built using commercial CFD software tool ANSYS 15.0 and the numerical fluid flow solver FLUENT. The actual floor contours of the longwall panel were used for developing of the CFD models. In these models, the working seam thickness is 3.6m, which also represents the face height. The longwall panel width is 300m and the roadway width on both maingate (MG) and tailgate (TG) sides of the face is 5.4m. The goaf height up to 80m above the working seam and the floor strata down to 12 m below the working seam is included in all the CFD models. In these models, MG and TG cut-throughs of 5m in width and 75m in length have also been incorporated, and these cut-throughs were spaced at 100m intervals along the panel in the CFD models. One rear shaft of 2.1m diameter is located near the start-up area of the panel. A number of goaf gas drainage holes of 0.3m diameter were also incorporated into the CFD models at different locations to investigate the effect of various goaf gas drainage strategies. One of the CFD models developed during the course of the project using field geometry and floor contours with panel length of 6km is shown in Figure 1.

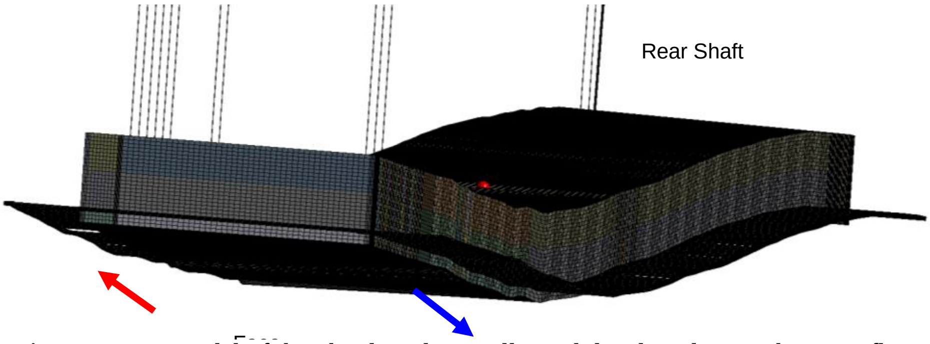

Figure 1 CFD model of the 6km long longwall panel developed using the seam floor contours

The field site has proposed to use rear shaft as intake to supply cool air directly to the face area in 6km long longwall panel to address high virgin rock temperature (VRT) and impractical issues related to rear shaft use as a return. Most of the simulations results presented in this paper were carried out with this proposed intake rear shaft ventilation layout, as shown in Figure 2. Velocity inlet boundary conditions were specified at the MG intake roadways and at the rear shaft inlet such that the total ventilation quantity of 60 m^3/s flows across the longwall face. From the rear intake shaft the ventilation quantity of 30 m^3/s flows towards the MG side roadways and enters the face and an additional 30 m^3/s flows from the MG intake. At the TG return, outflow boundary condition was specified in the modelling simulations.

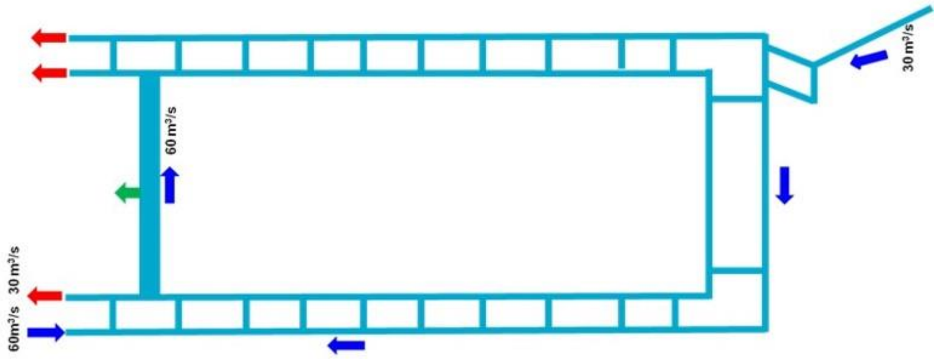

Figure 2 Longwall panel ventilation layout used in CFD models

3 MATHEMATICAL MODELS

Instantaneous conservative equations continuity, momentum and species transport equations were solved numerically using finite volume discretisation techniques. These equations were solved in the laminar flow goaf region which was treated as the porous media region with resistances varying in all the three directions. Porous media model in ANSYS FLUENT solver was used to simulate the flow though these regions by introduction of a source term to the standard fluid flow equations. The source term was composed of two parts: a viscous loss term (Darcy law), and an inertial loss term represented as in equation 4. Refer Ansys (2015) documentation manual 15.0 for any further information.

3.1 Instantaneous equations

Continuity equation

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

Steady State Navier Stokes Equation

$$(\vec{V} \cdot \nabla)\rho\vec{V} = -\nabla p + \mu\nabla^2\vec{V} + \rho\vec{f} + \vec{S} \tag{2}$$

Steady State Species Transport Equation

$$(\vec{V}_s \cdot \nabla)\rho Y_s = D_{ms}\nabla^2 Y + \dot{\omega}_s \tag{3}$$

where subscript s represents properties of O_2, CH_4 and N_2.

$$\vec{S} = -\left(\sum_{j=1}^{3} D_{ij}\mu\vec{V} + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho\left|\vec{V}\right|\vec{V} \right) \tag{4}$$

Source term in the momentum equation contributes to the pressure gradient in the porous cell, which is proportional to the fluid velocity in the cell. In the CFD model, the incorporation of goaf spatial permeability distribution and gas emission rates was via the user defined function (UDF) which was linked to the FLUENT solver.

3.2 Time Averaged Governing Equations

In the face region the flow was treated as turbulent and the time/Reynolds averaged equations were solved. Two equation standard k-epsilon model was used to determine the eddy viscosity and the Reynolds stress tensor.

Time averaged continuity equation:

$$\nabla \cdot \overline{\vec{V}} = 0 \tag{5}$$

Reynolds Averaged Navier-Stokes Equation:

$$(\overline{\vec{V}} \cdot \nabla)\rho\overline{\vec{V}} = -\nabla\overline{P} + \mu\nabla^2\overline{\vec{V}} + \nabla : \tau_R \tag{6}$$

where τ_R is the Reynolds stress tensor.

Turbulent Kinetic Energy- k equation:

$$\rho\overline{u}_j \frac{\partial k}{\partial x_j} = \tau_{ij}\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial}{\partial x_j}\left((\mu + \frac{\mu_T}{\sigma_k})\frac{\partial k}{\partial x_j} \right) - \rho\varepsilon \qquad (7)$$

where subscript *j* represents Einstein summation notation.

Turbulent dissipation- ε equation:

$$\rho\overline{u}_j \frac{\partial \varepsilon}{\partial x_j} = C_{\mu 1}\tau_{ij}\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial}{\partial x_j}\left((\mu + \frac{\mu_T}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j} \right) - C_{\mu 2}\rho\frac{\varepsilon}{k^2} \qquad (8)$$

where $C_{\mu 1}$ and $C_{\mu 2}$ are closure coefficient.

Reynolds Stress:

$$\tau_{ij} = \mu_T\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) - \frac{2}{3}\rho k\delta_{ij} \qquad (9)$$

where μ_T is the eddy viscosity and δ_{ij} is Kronecker delta.

Eddy Viscosity:

$$\mu_T = c_\mu \rho \frac{k^2}{\varepsilon} \qquad (10)$$

where c_μ is closure coefficient which is equal to 0.07.

Second order schemes are used to discretize the governing equations and the coupling between the pressure and velocity was done using SIMPLE algorithm. All the governing equations were solved until the convergence criteria of order 10^{-5} is reached.

4 GOAF GAS FLOW PATTERNS

Extensive CFD modelling simulations have been carried out to obtain a fundamental understanding of goaf gas flow patterns in longwall panels, under field site conditions.

CFD modelling studies involved simulation of goaf gas flow patterns with panel retreat up to 500m, 1km, 3km and 6km to simulate goaf gas flow patterns in start-up areas and in longer longwall panels under different goaf gas emission scenarios of 1,000 l/s and 2,000 l/s.

4.1 500m start-up model

To obtain a fundamental understanding of the goaf gas distribution flow patterns in the start-up area, simulations were carried with the 500m long model. In all the base case simulations, the ventilation air quantity flowing across the face was around 60 m^3/s, and rear shaft was used as intake shaft with around 30 m^3/s airflow as shown in Figure 2. Goaf gas emission rate was specified as 1,000 l/s in all base-case simulations for reference and comparison purposes. Results of the base-case simulation presented shows the goaf oxygen gas distribution in a section across the plane which lies in the seam and is 2m above the floor.

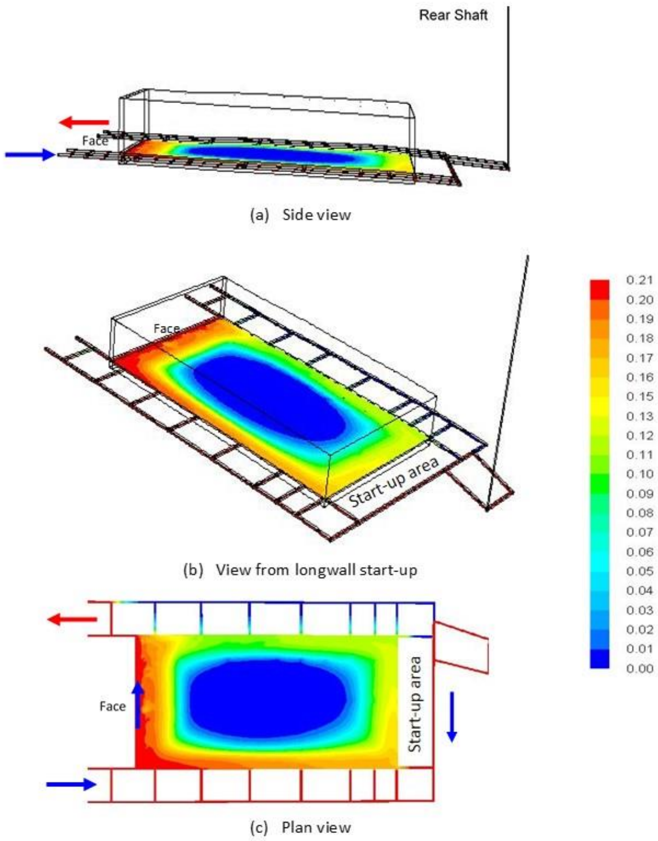

Figure 3 Oxygen distribution in the goaf - 500m start-up model

Simulation results indicate that the oxygen ingress into the goaf area would be very high during extraction of start-up areas in the longwall panels, as shown in Figure 3. Results indicate very high oxygen gas distribution of 21% up to 150m behind the face on the MG side and varied between 15% - 18% in the start-up areas of the goaf. Analysis of results indicate that flat seam gradient is a major factor for high oxygen ingress into the goaf area, particularly in the start-up areas of the panel. It is to be noted that in the 500m long start-up model, the working face line is 22 m above (higher elevation) the start-up line.

The methane gas distribution in the 500m long goaf is shown in Figure 4. Results indicate that methane gas distribution in the start-up area will be symmetrical and widely distributed across the goaf area, with highly concentration at the centre of the goaf due to flat seam gradient. Methane gas distribution of this kind would pose significant challenges for goaf gas drainage in the start-up areas of the panel.

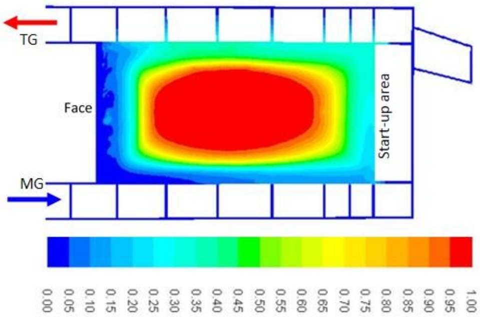

Figure 4 Methane distribution in the goaf – 500m model

4.2 **1km model**

In the 1km long model, the total elevation difference between the start-up line and the working face line is 36m with the face positioned at higher elevation. Figure 5 shows the oxygen distribution in 1 km long goaf in a plane at 2m above the seam floor in various views. Results show that oxygen ingress into the goaf decreased significantly in 1km model when compared with the 500m long start-up model. However, it is to be noted that oxygen levels in the goaf are still high at more than 15% at 300m behind the face. Low goaf gas emission rate of 1000 l/s is also one of the contributing factors for high oxygen content into the goaf, in addition to the panel geometry, seam gradient and the ventilation design parameters. Gas distributions with higher goaf gas emission rates of 2000 l/s are presented in the later sections in this paper.

Results indicate that although the oxygen distribution levels at start-up area would be significantly lower for 1km long goaf when compared with 500m long goaf, the oxygen levels are more than 10% in the start-up area in the 1km long goaf. High oxygen levels in the start-up area of the panel can also be attributed to high goaf permeability, steep down dip of the panel and rear intake shaft. Analysis of the results showed that intake airflow seems to have major influence on seam level gas distribution up to 200 – 250m behind the face and beyond that gas buoyancy seems to play a major role on goaf gas distribution.

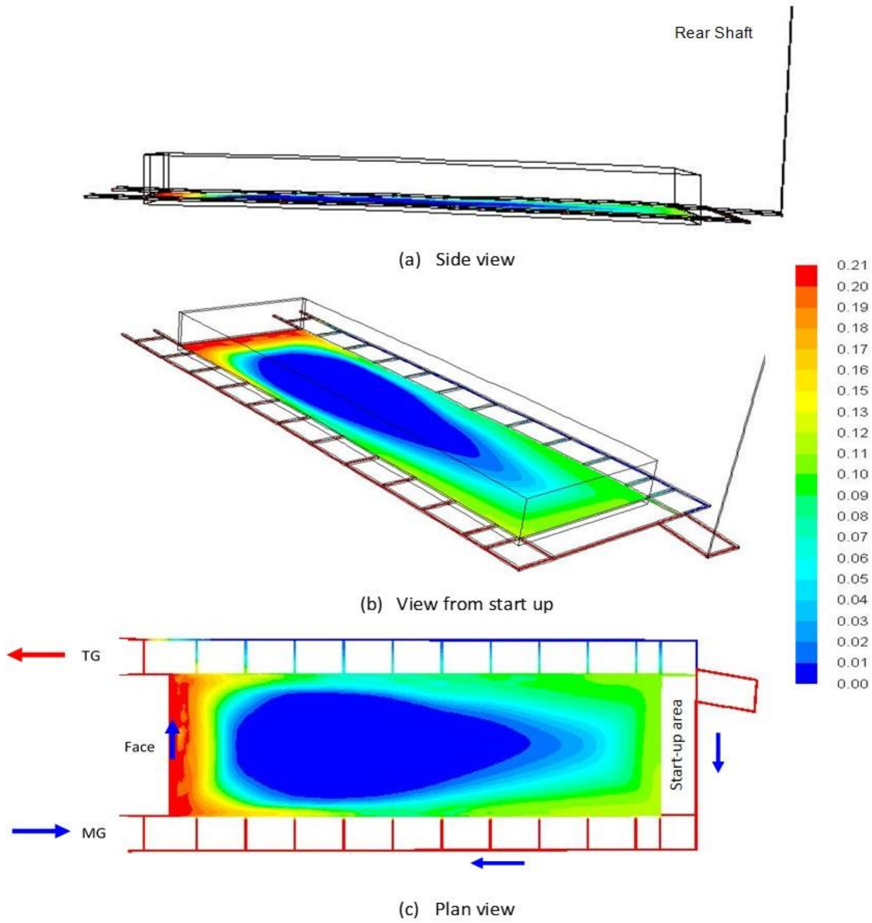

Figure 5 Oxygen distribution in the goaf – 1 km model

The methane gas distribution in Figure 6 indicated symmetric and wide distribution of gas near the start-up area, similar to the 500m long start-up model, with high concentration of gas located at the centre of the goaf due to flat seam gradients. As suggested earlier, methane gas distribution profile indicates significant challenges for goaf gas drainage and suggests that there is a need for supplementary goaf gas drainage holes in the start-up area or on the MG side of the goaf, in addition to the standard TG side goaf holes.

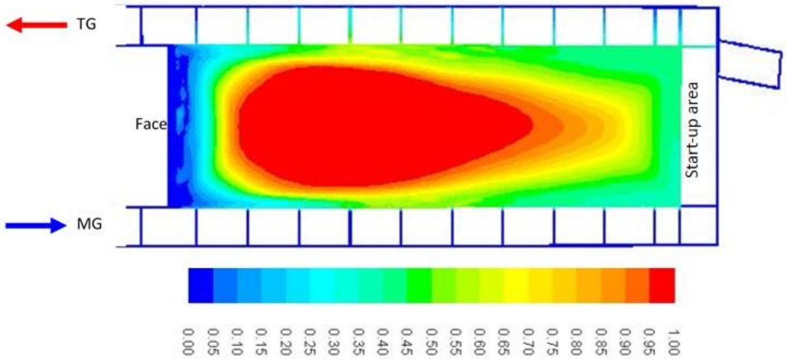

Figure 6 Methane distribution in the goaf – 1km model

4.3 3km model

For the 3 km long goaf model, the elevation difference from the start-up line till the middle of the goaf is 45m and thereafter elevation difference from the middle of the goaf till the face line is only 15m. In total, the elevation difference from the start-up line of the panel to the working face line is 60 m for 3 km long goaf.

The simulation results indicate that oxygen concentration on the MG side of the goaf would be high at more than 10% under the low goaf gas emission scenario of around 1,000 l/s, as shown in Figure 7. Results indicate that oxygen concentration in the start-up areas of the panel would be particularly high due to seam geometry, flat seam gradients at the start-up area of the panel and ventilation system with rear intake shaft.

In Figure 8, results indicate that in 3km long goaf of the panel, the methane gas distribution would be skewed towards the TG side of the goaf and towards the face area due to substantial change in seam gradients. This methane gas distribution profile assists traditional goaf gas drainage practice with goaf holes on the TG side of the goaf.

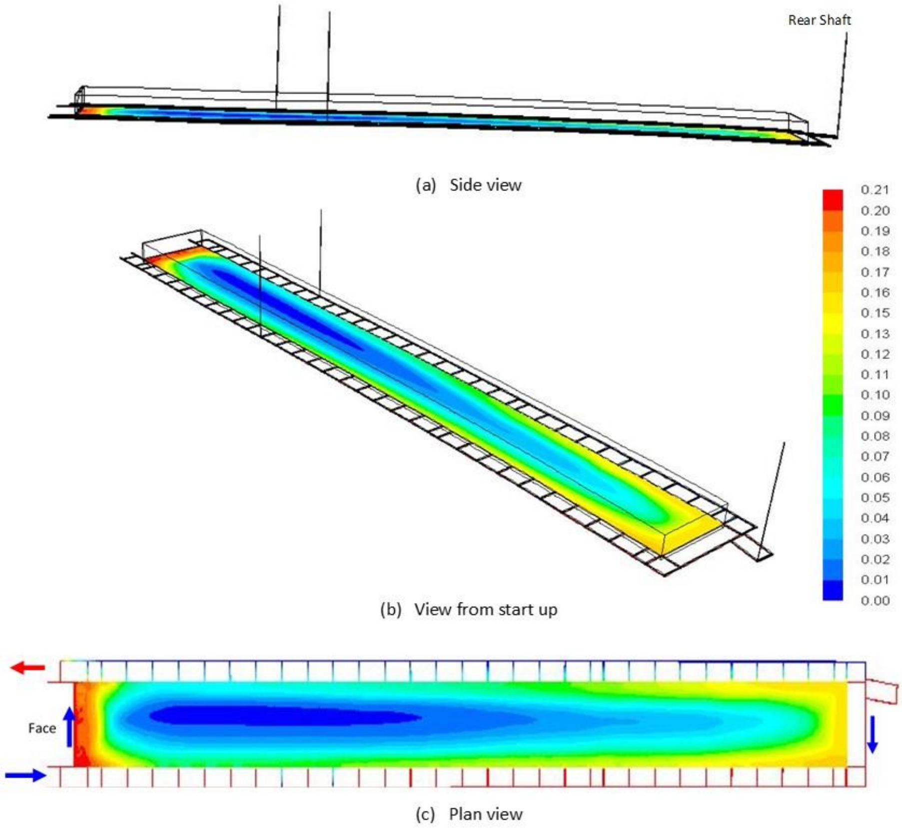

Figure 7 Oxygen distribution in the goaf – 3 km model

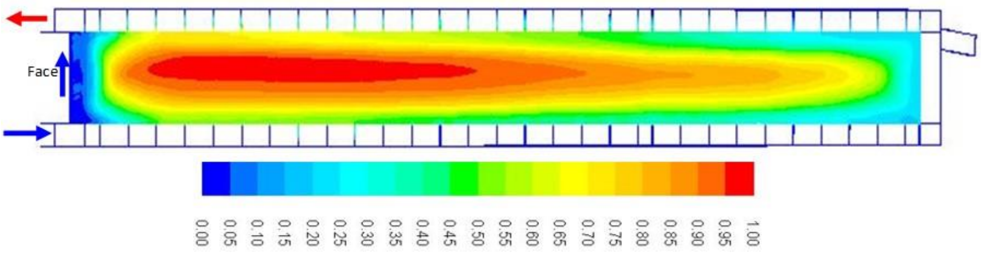

Figure 8 Methane distribution in the goaf – 3 km model

4.4 6km model

The total elevation from the face line till the start-up line of the panel is 225 m for the 6km long panel. Panel has steep gradient in the last 3km section of the panel, with an elevation difference of 165 m whereas the total elevation difference in the first 3km section of the panel is only 60m. In Figure 9, the oxygen concentration on the MG side of the goaf has more than 15% under the low goaf gas emission scenario of around 1,000 l/s. Results indicate that oxygen concentration in the first 4.0km of the panel from the start-up area would be particularly high due to seam geometry and gas buoyancy effects, as most of the methane gas migrates to the last 2.0km of the panel near the face due to steep gradient in that last 2km of the longwall panel.

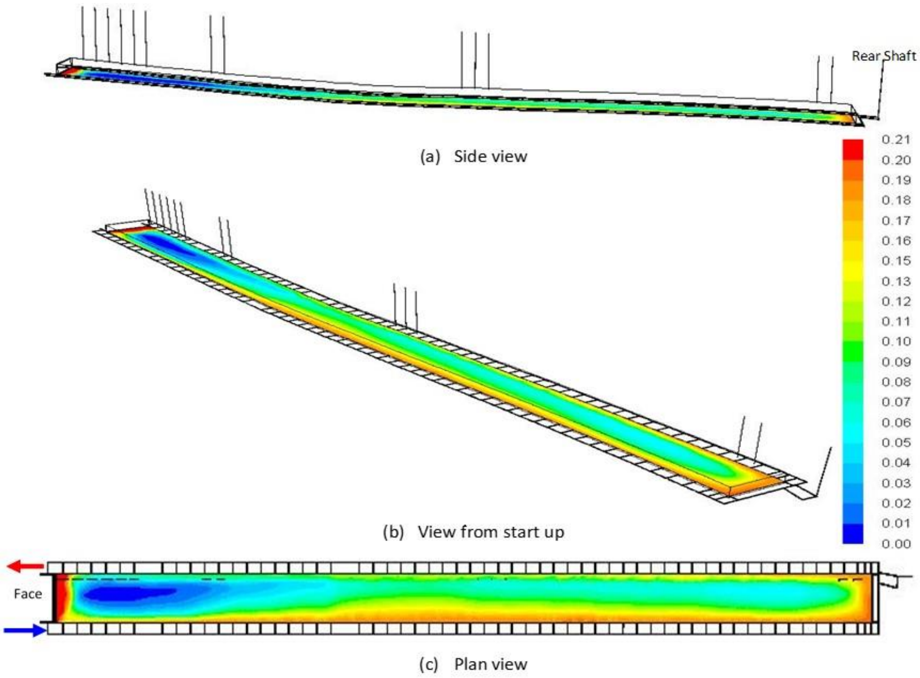

Figure 9 Oxygen distribution in the goaf - 6 km model

Figure 10, results indicate that in 6km long goaf, the methane gas distribution would be significantly skewed towards the TG side of the goaf and towards the face due to steep seam gradients in the second half of the panel towards the face line. This methane gas distribution profile assists traditional goaf gas drainage practice with goaf holes located on the TG side and indicates that goaf gas drainage would be easily manageable in long panels.

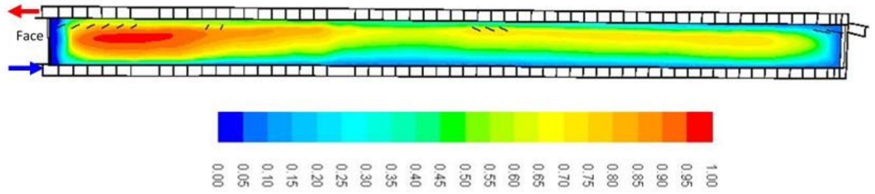

Figure 10 Methane distribution in the goaf - 6 km model

5 HIGH GAS EMISSION RATE OF 2000 L/S

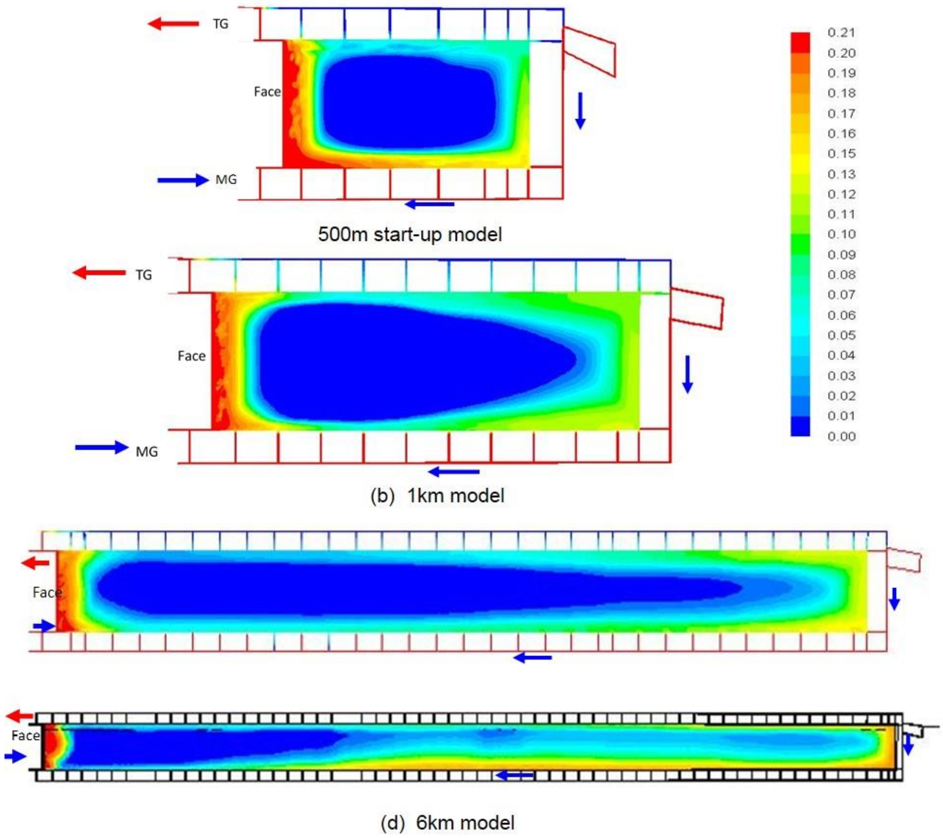

Figure 11 Oxygen distribution for various goaf lengths with 2000 l/s gas emission rate

CFD model results with goaf gas emission rate of 2000 l/s of pure methane for various goaf lengths are presented in Figure 11. Analysing the results show that an increase in the goaf gas emission rate from 1000 l/s to 2000 l/s significantly reduced the oxygen concentration levels and distribution spread in the goaf area, with concentration levels at the start-up of the panel ranging between 10% – 15% as shown in Figure 11(a). However, the oxygen ingress on the MG side of the goaf is high with concentration varying between 16% – 21%. Overall, results indicate that oxygen ingress into the goaf in the start-up area would be high for low to moderate goaf gas emission rates of up to 2,000 l/s.

For 1km long goaf, Figure 11(b), the oxygen ingress into the goaf decreased significantly when compared with 500m long model, although oxygen concentration levels in the start-up area are high at more than 10% due to flat seam gradients. Oxygen ingress into the goaf behind the face on the MG side has reduced significantly with 2,000 l/s goaf gas emission rate in comparison with oxygen ingress in 1km model with 1,000 l/s of goaf gas.

Figure 11(c) shows that oxygen ingress into the goaf reduced significantly with 2,000 l/s goaf gas emission rate when compared with the base case results in the 3km long goaf model. The oxygen concentration level was around 6% - 8% for most of the goaf on the MG side, except near the start-up area of the goaf, where it increased to more than 10% due to flat seam gradient, panel geometry and gas buoyancy.

Figure 11(d) shows the oxygen distribution in the 6 km long goaf for goaf gas emission rate of 2000 l/s. Similar to other models, oxygen ingress into the goaf in 6km model has also reduced significantly with 2,000 l/s goaf gas emission rate when compared with base-case (1,000 l/s goaf gas emission rate) results.

6 CONCLUSION

Three-dimensional CFD models have been developed for fundamental understanding of the goaf gas flow patterns in the start-up area and in longer goaf areas as the face retreats from 500m to 1km, 3km and 6km lengths. The simulation results indicate that oxygen concentration on the MG side of the goaf would be generally high at more than 10% under the low goaf gas emission scenario of around 1,000 l/s. Results indicate that oxygen concentration in the start-up area of the panel would be particularly high due to flat seam gradients. Although the oxygen ingress into the goaf was reduced significantly in longer 1km, 3km and 6km goaf models, the oxygen levels were still high above 10% in the start-up area of the panel. Analysis of the results showed that intake airflow seems to have major influence on seam level gas distribution up to 200 – 250m behind the face and beyond that gas buoyancy seems to play a major role on goaf gas distribution. Results from 6km model indicate that oxygen concentration in the first 4km section of the panel from the start line of the panel would be particularly high due to seam geometry and gas buoyancy effects, as most of the methane gas migrates to the last 2km section of the panel nearer to the face due to steep gradient in that last section of the longwall panel.

7 REFERENCES

ANSYS (2015) *ANSYS FLUENT.* [Software] Version 15.0.

AZIZ, N., BALUSU, B. and BAAFI, E. (1993). Application of Computational Fluid Dynamics Codes to Develop Effective Gas/Dust Control Measures in Underground Coal Mines. *The Australian Coal Journal,* 42, pp. 19–27.

BALUSU, R. et al. (2002a) An investigation of the gas flow mechanics in longwall goafs. In: *9th US Mine Ventilation Symposium, Kingston, Ontario, Canada, June 2002*. pp. Rotterdam: AA Balkema Publishers, 443-450.

BALUSU, R. et al. (2004) Optimisation of goaf gas drainage and control strategies. *ACARP Project C10017, CSIRO Exploration and Mining Report 1186F*, June 2004.

BALUSU, R. et al. (2001) Goaf gas flow mechanics and development of gas and sponcom control strategies at a highly gassy coal mine. *Australia-Japan Technology Exchange Workshop, Hunter Valley, Australia, 18.*

BALUSU, R. et al. (2004) Optimisation of Longwall Goaf Gas Drainage and Control System, *ACARP Report No: C10017.*

BALUSU, R. et al. (2002b) Optimum Inertisation Strategies. In: *Proceedings of the Queensland Mining Industry Health and Safety Conference, Townsville, Australia.* pp. 133 – 144.

BELLE, B. (2015) Innovative tailgate mobile goaf gas management in two gateroad longwall panels – concept to implementation. In: *The Australian Mine Ventilation Conference, Sydney, Australia, September 2015.*

ROY, M. et al. (2010) Strategic review of gas management options for reduced GHG emissions. *ACARP Report No: C17057.*

TANGUTURI, K., BALUSU, R. and RAMAKRISHNA, M. (2014) CFD Modeling of Methane Gas Distribution and Control Strategies in a Gassy Coal Mine. *The Journal of Computational Multiphase Flows,* 1, pp. 65-77.

TANGUTURI, K. et al. (2013) Effect of buoyancy on methane gas distribution and gas control strategies at tailgate region in a gassy coal mine. In: *9th International Conference on CFD in the minerals and process Industries, Melbourne, December 2013*. pp. 1-6.

TANGUTURI, K. and BALUSU, R. (2015) Fundamental understanding of goaf gas displacement in longwall goaf. *Iranian Journal of Mining & Environment*, 2, pp 191-203.

YARLAGADDA, S., BALUSU, R., and VEERAREDDY, B. (2011) Proactive Strategies for Prevention and Control of Fires in Bord and Pillar Mines Working in Thick Coal Seams, *The Australasian Institute of Mining and Metallurgy*, pp. 249 – 256.