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INERTISATION OF HIGHWALL MINING TO CONTROL METHANE CONCENTRATIONS AT THE MOURA MINE

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ABSTRACT

Methane, a highly explosive gas, which is released during coal mining, presents an imminent problem when mixed with oxygen in regard to maintaining safe working conditions. The Moura Mine's previous highwall coal mining operation in Central Queensland identified that production rates and penetration depths of mining equipment has been restricted for mines with high methane concentrations in comparison to regions with lower methane concentrations. A number of inert gases have been identified to inertise the highwall drive, including Carbon Dioxide, Nitrogen and Boiler Gas, which is a combination of carbon dioxide, oxygen and nitrogen. The objective of this paper is to determine which of these gases is the most effective in improving the mine's efficiency with regard to safety and production rates at a chosen penetration depth of 300m. A 2D, steady, non-reacting species transport model of the highwall drive was used to obtain methane and oxygen concentrations using CFD software (Fluent). Results indicate that applying the inert gases at high angles is more effective in minimising the methane/oxygen concentrations within the drive than at lower angles. Carbon Dioxide was the most effective when applied at a 60 degree angle, followed closely by Nitrogen, while Boiler Gas came last.

NOMENCLATURE

Y_i	*species mass fraction*
R_i	*net rate production of species by chemical reaction*
S_i	*net rate creation of species from a dispersed phase*
J_i	*diffusion flux of a species, i*
ρ	density
D_t	*turbulent diffusivity*
μ_t	*turbulent viscosity*
Sc_t	*Schmidt number*
a	characteristic length
p	pressure
$\mathbf{v}$	time averaged velocity
μ	dynamic viscosity
ρg	gravitational body force
$\bar{\bar{\tau}}$	stress tensor

INTRODUCTION

The Moura Mine in Central Queensland was the first coal mine in Australia to introduce the highwall mining method. This method was developed so that additional coal could be extracted via surface mining operations after reaching the economic limit of opencut operations. The two main highwall mining systems currently used in Australia are the Addcar Highwall Mining system and the Auger system. Previously, the Moura Mine's highwall mining operation used the Addcar Steep Dip Highwall Mining system, a modified Mining Technologies Addcar Highwall Mining system with the remote controlled Joy 12CM12B continuous miner. This system has a maximum penetration depth of 360 metres having a cut profile 3.6 metres wide by 3.7 metres high. According to the *Anglo Coal: Moura Coal Mine,* (2005), the miner is capable of producing 720t/h, an equivalent to 1.6Mt/y of run-of-the-mine-coal.

Methane released from the coal during mining is highly explosive when mixed with oxygen at certain levels and requires constant monitoring to ensure the health and safety of both personnel and equipment. The Moura Mine was considered to be a 'gassy' mine, meaning there were large quantities of methane found within the coal seam. It was identified that as penetration depths of highwall mining equipment continued to increase, this led to more frequent encounters with methane. This was particularly so in the northern side of the mine which had high methane concentrations in comparison to the southern side and penetration depths were restricted to 160m in comparison to the 360m in the low methane concentration regions (Kunst, G personal. comm., (2006)). There are three approaches to prevent methane ignitions under these circumstances: control of the ignition source, diluting the methane to a safe level and effectively monitoring methane levels with an automatic shutdown mechanism on equipment when explosive methane concentrations exist. The Moura Mine took the third option by developing a gas management plan in regard to safe working levels of methane/oxygen which was based on the Coward Triangle Gillies and Jackson, (1998), relating methane and oxygen concentrations to the mixture's flammability limits.

Volkwein, J. (1997) reported on the trials of injecting inert Boiler Gas from the drive unit of an Auger highwall operation to decrease the incidence of ignitions during mining. Hand-held monitors were used to record methane/oxygen concentrations at the surface. He concluded that it was an effective means to decrease the incidence of ignitions. CFD modelling was applied to the gas emission and migration by Ren, T. Edwards, J. and Jozefowicz, R. (1997) which considered the movement of methane through the coal seams in an underground mining operation. The CFD analysis was then related to actual results in order to validate the CFD results. It is essential for mines to accurately predict methane emissions in order to design effective inertisation. This study also identified that further research in the prediction of gas migration within adjacent areas would benefit the control of methane within underground mines.

The highwall system uses inert gases injected into the highwall drive during mining to maintain safe methane levels and has been found to be effective at predetermined penetration depths for the various regions of the mine. Three commercially available inert gases have been identified for use in the highwall systems: these are Nitrogen (N_2), Carbon Dioxide (CO_2) and Boiler Gas. Boiler Gas is generated from a combustion process to burn off any oxygen present in the air and generally consists of 85% Nitrogen (N_2), 14% Carbon Dioxide (CO_2) and 1% Oxygen (O_2). Determining which of these gases is most effective and the level of inertisation in maintaining methane concentrations within safe working limits has the potential to improve safety, productivity, cost and penetration depths of the current highwall system.

MODEL DESCRIPTION

Governing Equations

The flow of the different gases in the highwall mine such as Methane, Oxygen, Carbon Dioxide and Nitrogen is governed by the mass conservation and momentum laws. The mass conservation equation of the chemical species, which is a convective-diffusion equation that helps to predict the mass fraction, Y_i, of the different species, i, is given in Equation 1,

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + S_i \qquad (1)$$

where, $\vec{v}$ is the time-averaged velocity vector, $\vec{J}_i$ is the diffusion flux of species i, ρ is the fluid's density and S_i is the rate of creation of a species, i, by addition from the dispersed phase. For turbulent flow, the diffusion flux $\vec{J}_i$ is given by Equation 2,

$$\vec{J}_i = -\left(\rho D_{i,m} + \left(\frac{\mu_t}{Sc_t}\right)\right)\nabla Y_i \qquad (2)$$

where Sc_t is the turbulent Schmidt number defined as $\frac{\mu_t}{\rho D_t}$, where μ_t is the turbulent viscosity and D_t is the turbulent diffusivity. If we have an N number of species, we need to solve N-1 equations, since the mass fraction of all species needs to add up to one.

The momentum equation for turbulent flow, which is called the Reynolds-Averaged Navier-Stokes Equation, is given as:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = \rho\vec{g} - \nabla p + \nabla.(\bar{\bar{\tau}}) + \nabla.(-\rho \overline{\vec{v}'\vec{v}'}) \qquad (3)$$

where $\rho\vec{g}$ is the gravitational body force, p is the static pressure, $\nabla.(-\rho \overline{\vec{v}'\vec{v}'})$ is the Reynolds stresses, which depends on the turbulence model chosen, and $\bar{\bar{\tau}}$ is the stress tensor which is given as follows:

$$\bar{\bar{\tau}} = \mu\left[\left(\nabla\vec{v} + \nabla\vec{v}^T\right) - \frac{2}{3}\nabla.\vec{v}I\right] \qquad (4)$$

where, μ is the fluid's viscosity, and I is the identity matrix. The turbulent model chosen in the work is the k-Є realisable model. The term "realisable" means that the model satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows (Shih, et al. 1995). This turbulent model provides superior performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation and recirculation. The non-equilibrium wall function was chosen to include the pressure-gradient effects. The wall-neighbouring cells are assumed to consist of a viscous sub-layer and a fully turbulent layer (Kim & Choudhury (1995)). The first order discretisation for momentum, turbulent kinetic energy and turbulence dissipation rate was assumed, except for the pressure for which the PRESTO (PREssure STaggering Option) discretisation was chosen since it is more appropriate for flow with curvature (Patankar 1980). The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm (Versteeg & Malalasekera (2007)), was chosen for the velocity pressure coupling. Properties of the mixture of gases, such as density and viscosity, were chosen to be evaluated from the ideal gas mixing laws and mass diffusivity was estimated based on the kinetic theory (Hirschfelder et al. (1954)).

Geometry of the Problem

Ideally a 3–D model is needed to accurately predict the flow of the different gases in the highwall drive, however since the geometry is 300 m long and 3.6 metres wide and a large depth, 3 –D effects are minimal, apart from close to the head of the machine. A two-dimensional model was generated for the highwall drive at a working depth of 300m, with a pit at the inlet of the highwall drive of a rectangular shape which has a 17.23m depth and 19.5m width, Figure 1. Figure 2 and Figure 3 give the details of the head part and the pit part respectively. The geometry of the model was based on the cutting profile of the equipment and its available dimensions. The inert gas was injected 15m from the working face (coal face, Figure 2), as in the actual previous mining operation. The inert gas was injected at three different angles: 0, 30 and 60 degrees with respect to the normal direction to the gas outlet. The inert gas flow rate was chosen to be 1.275 m^3/s and was kept constant in all cases. Methane gas was assumed to be generated from the coal face at 0.0166 m/s and coal floor at 0.06 m/s, based on previous measurements. Methane generation from the drive roof and the floor was not included in the model. The boundary condition at the pit top was assumed to be at standard atmospheric pressure.

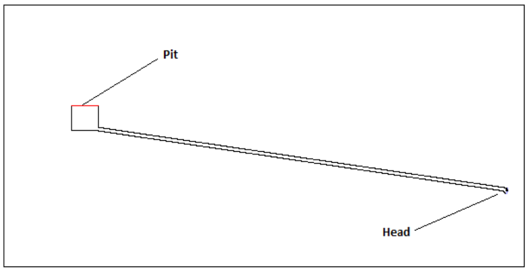

Figure 1: Schematic diagram of the higwall mine.

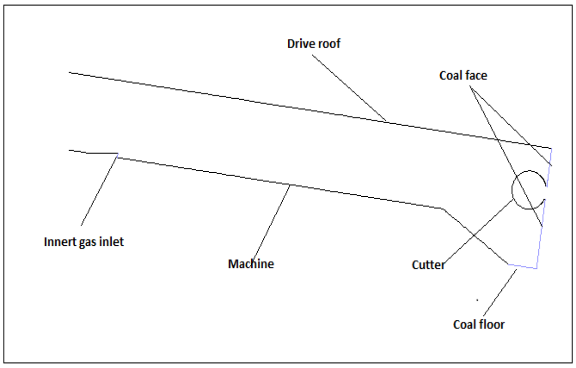

Figure 2: Schematic diagram of the Head.

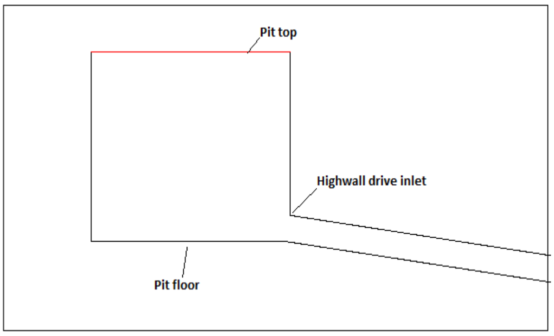

Figure 3: Schematic diagram of the Pit.

RESULTS

In order to validate the numerical model; three different mesh sizes were investigated. The mesh sizes for the model consisted of 229,494 (coarse), 320,774 (medium) and 421,776 (fine) nodes. The mass fraction of the Methane at the pit top when using Boiler Gas at 0 degrees were compared and given in Figure 4. Results show small variation as the mesh size changes which proves that the solution obtained is almost independent of the mesh size.

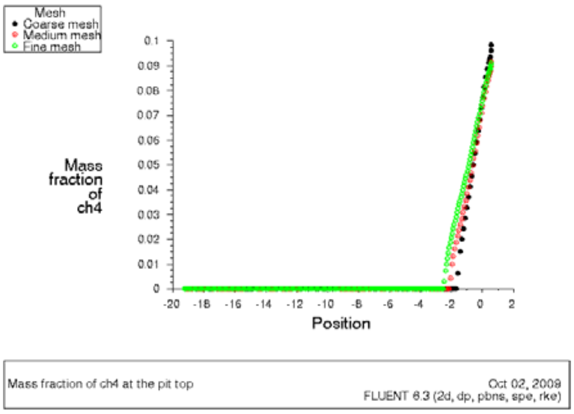

Figure 4: Convergence of the methane fraction at the pit top as finer mesh has been used.

Three different inert gases were used in this work to identify which is the most effective in maintaining safe mining operations. These are Nitrogen, Carbon Dioxide and Boiler Gas. Boiler Gas, in particular, was chosen since it was readily available. These results were produced using the model mesh with 320,774 nodes.

A comparison of the mass fraction of Methane and Oxygen using the three different inert gases at three different angles of application was made at two different locations. The first location was at the pit top, i.e., at the outlet of the highwall drive, where monitoring is usually conducted to check whether operations are safe to continue or whether a shut-down is necessary and these results are shown in Figures 5 - 10. In all these figures the position is measured in meters from the inlet of the highwall drive.

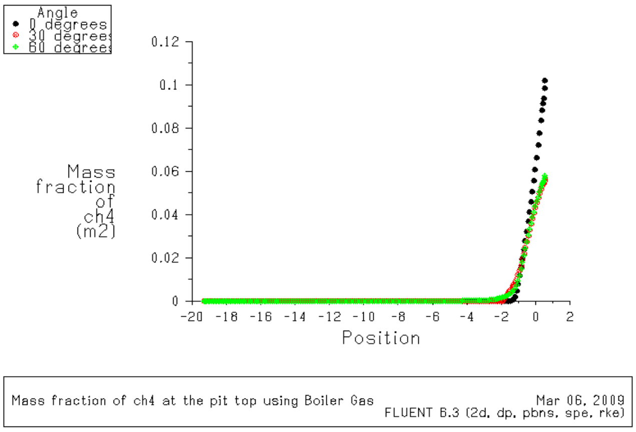

Figure 5: Comparison of Methane concentrations at the pit top using Boiler Gas at different angles of application.

Investigating the Methane mass fraction at the pit top, using Carbon Dioxide, Nitrogen and Boiler Gas, shows that, as the inert gas angle of application increases, a drop in the Methane mass fraction occurs, as shown in Figures 5, 7 and 9, accompanied by an increase in the Oxygen mass fraction, as shown in Figures 6, 8 and 10.

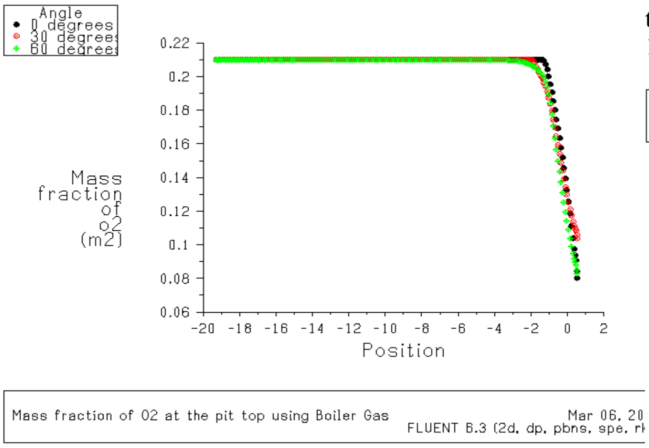

Figure 6: Comparison of Oxygen concentrations at the pit top using Boiler Gas at different angles of application.

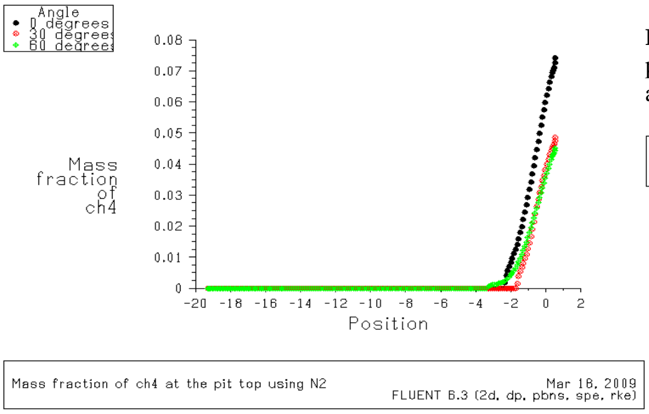

Figure 7: Comparison of Methane concentrations at the pit top using Nitrogen at different angles of application.

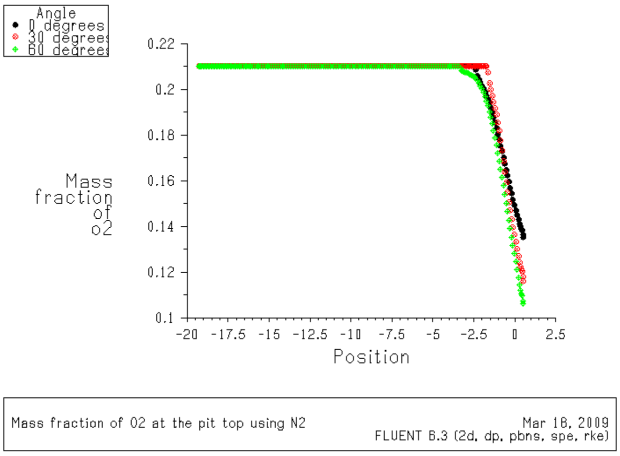

Figure 8: Comparison of Oxygen concentrations at the pit top using Nitrogen at different angles of application.

A comparison of the mass fraction of Methane and Oxygen at the second location, along the drive roof, is given in Figures 11 - 16. Again the position is measured in meters from the inlet of the highwall drive.

Investigating the mass fraction of methane along the drive roof, using the three inert gases at the three different angles, shows that as the inert gas angle of application increases, a drop in the Methane mass fraction occurs throughout the majority of the drive, as shown in Figures 11, 13 and 15.

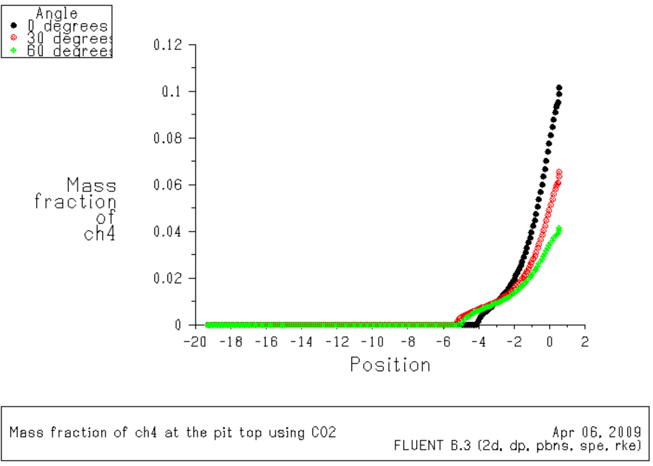

Figure 9: Comparison of Methane concentrations at the pit top using Carbon Dioxide at different angles of application.

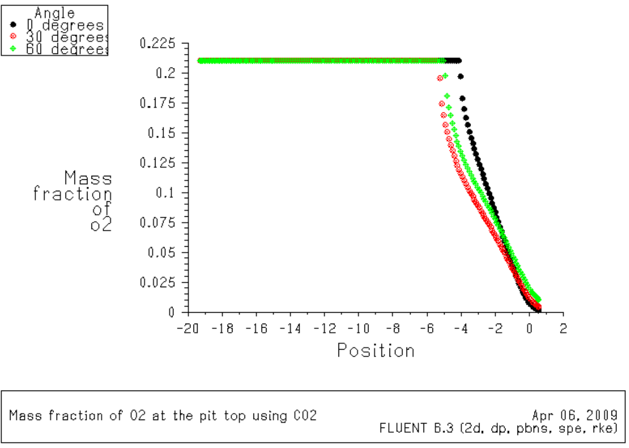

Figure 10: Comparison of Oxygen concentrations at the pit top using Carbon Dioxide at different angles of application.

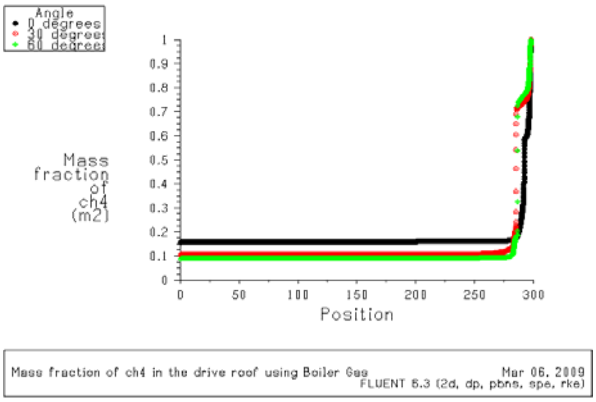

Figure 11: Comparison of Methane concentrations along the drive roof using Boiler Gas at different angles of application.

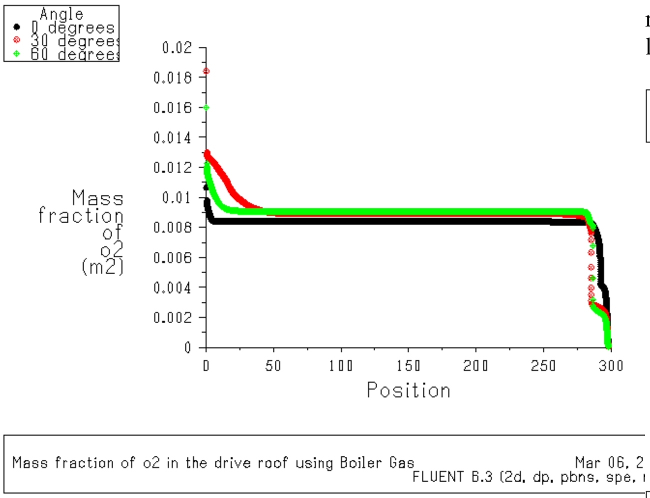

Figure 12: Comparison of Oxygen concentrations along the drive roof using Boiler Gas at different angles of application.

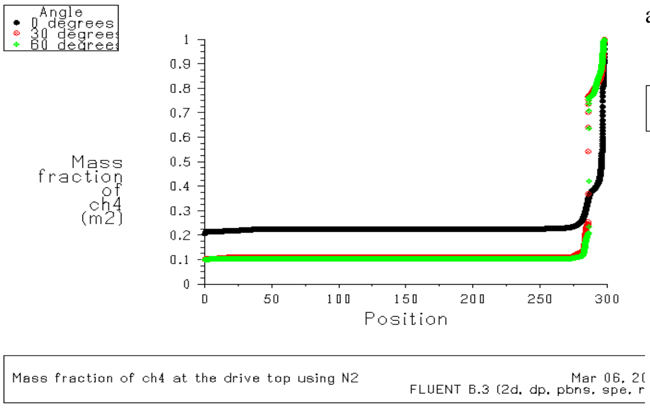

Figure 13: Comparison of Methane concentrations along the drive roof using Nitrogen at different angles of application.

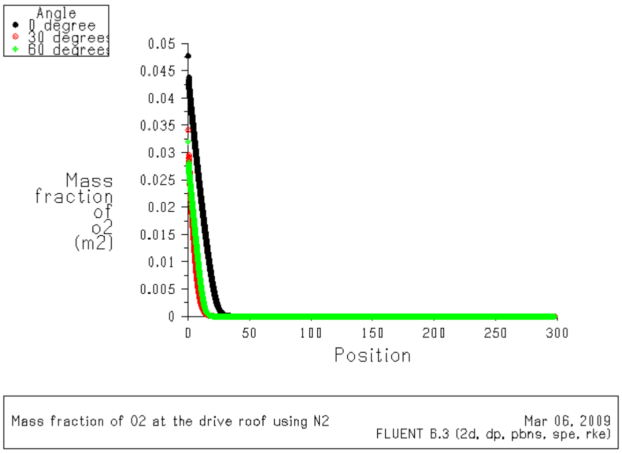

Figure 14: Comparison of Oxygen concentrations along the drive roof using Nitrogen at different angles of application.

However, the opposite effect was observed near the machine head, as was expected, since the lowest angle (0 degrees) produces a flow parallel to the floor, hence reaching the machine head more effectively, in turn lowering the Methane mass fraction.

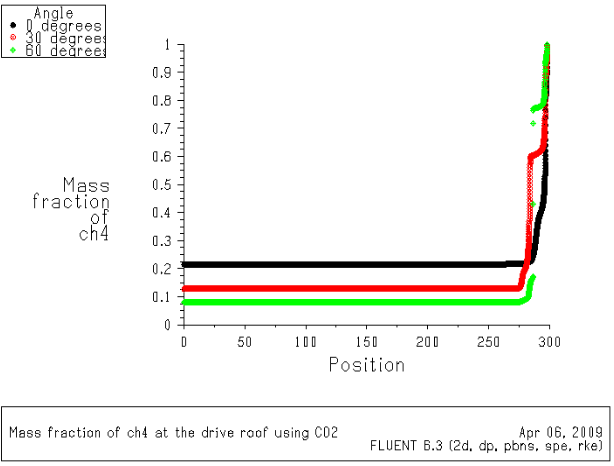

Figure 15: Comparison of Methane concentrations along the drive roof using Carbon Dioxide at different angles of application.

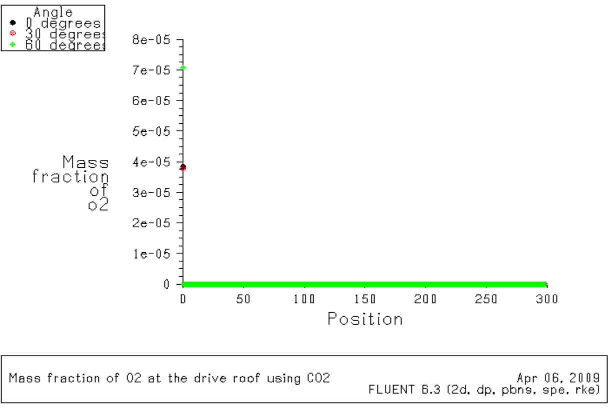

Figure 16: Comparison of Oxygen concentrations along the drive roof using Carbon Dioxide at different angles of application.

In comparing the three inert gases, it appears that the application of Carbon Dioxide at 60 degrees provides the most effective control of Methane within the drive since it has the lowest mass fraction of methane, Figure 15. It is to be noticed that along the drive roof, the mass fraction of Oxygen is zero for all angles of application using the Carbon Dioxide as shown in Figure 16. This can be attributed to the heavy molecular weight of Carbon Dioxide in that it inhibits outside Oxygen from penetrating into the drive. In comparing the gases, Nitrogen was found to be second most effective and Boiler Gas least effective.

According to Gillies and Jackson (1998), Coward determined a methane/oxygen relationship from empirical data which indicates whether mixtures of Methane and Oxygen have reached explosive levels, and this can be applied to coal mining operations. According to the Coward Triangle, when Methane concentrations are 5% or lower, Oxygen concentrations are not critical to producing a potentially explosive mixture. However, if the Methane percentage increases beyond 5%, the percentage of Oxygen permitted must be maintained below 12% in order to prevent an explosive mixture from occurring. Thus, in order to determine the inert gas that maximises the safety of highwall mines, a combination of Methane and Oxygen must be examined in each case modelled. From Figures 6, 8 and 10 one can observe that when Methane has the highest concentration at the pit top, Oxygen has the lowest concentration. Table 1 shows a summary of the maximum Methane concentrations and the minimum Oxygen concentrations derived from the model at the pit top location.

Maximum Methane % Concentrations			
Inert Gas	0 degrees	30 degrees	60 degrees
Carbon Dioxide	10.2	6.6	4.2
Nitrogen	8.8	5.2	4.5
Boiler Gas	9.7	6.2	6.0
Minimum Oxygen % Concentrations			
Inert Gas	0 degrees	30 degrees	60 degrees
Carbon Dioxide	0	0	0.01
Nitrogen	13.6	12	11.7
Boiler Gas	12.8	11	8.2

Table 1: Methane and Oxygen percentages at the pit top location.

Examining the above results, it appears that the CO2 and N2 gases, when injected at 60 degrees, meet the requirements of the Coward Triangle for a non-explosive zone, while the Boiler gas closely satisfies the safe conditions. Carbon Dioxide at the 60 degrees seems to be the most effective in reducing Methane concentrations; Nitrogen appears to be the second most effective while Boiler Gas appears to be the least effective.

Along the drive roof, the Methane level is higher than 5% in all cases, but Carbon Dioxide is the only inert gas that produced an Oxygen concentration of 0% in this location, providing, once again, the most effective control within the drive. Table 2 shows a summary of these results within the drive. It is to be noted that even N2 gave higher % of O2 in the drive than the boiler gas, these higher rates were confined only to the zone close to the inlet of the drive.

Methane % Concentrations in majority of the drive			
Inert Gas	0 degrees	30 degrees	60 degrees
Carbon Dioxide	23.4	12.8	8.1
Nitrogen	20.7	10.8	9.1
Boiler Gas	15.8	10.8	9.1
Maximum Oxygen % Concentrations			
Inert Gas	0 degrees	30 degrees	60 degrees
Carbon Dioxide	0	0	0
Nitrogen	4.8	3.4	3.2
Boiler Gas	1.1	1.8	1.6

Table 2: Methane and Oxygen percentages along the drive roof.

CONCLUSION

The application of any of the three inert gases trialled in this study at a high angle appears to be capable of maintaining Methane concentrations at safe levels at the pit top. A comparison of the three inert gases, namely Carbon Dioxide, Nitrogen and Boiler Gas, shows that Carbon Dioxide is the most effective in reducing Methane concentrations when applied at 60 degrees. At the pit top Methane concentration were within safe levels (methane maximum % concentration was below 5%) and within the drive while methane was higher than the 5% limit (8.1%) it was combined with 0 % Oxygen, which is still a safe combination. Nitrogen is the second most effective and Boiler Gas is the least effective. Safety near the machine head was not considered in detail in this study. However, it appears that another application of inert gas at zero degrees may improve safety at that location. It is recommended that two inert gas injection points to be utilised: one at 60 degrees to the normal direction of the gas outlet with a high flow rate and another at zero degrees, with a much smaller flow rate to maintain low methane levels at the machine head.

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