2016

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Publication Details
Hua Guo, Clint Todhunter, Qingdong Qu, Hamish Kerr and Johnny Qin, An Innovative Drainage System for Coal Mine Methane Capture Optimisation and Abatement Maximisation, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 16th Coal Operators' Conference, Mining Engineering, University of Wollongong, 10-12 February 2016, 380-393.
AN INNOVATIVE DRAINAGE SYSTEM FOR COAL MINE METHANE CAPTURE OPTIMISATION AND ABATEMENT MAXIMISATION

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ABSTRACT: Gas drainage in Australian longwall mining is increasingly challenging because of complex gassy conditions, multi-seam environments, and environments where drilling a large number of conventional surface vertical gas drainage boreholes is not practical. This paper presents an alternative approach, using horizontal boreholes for longwall goaf gas drainage. This horizontal drainage method has been trialled successfully at the Blakefield South mine. The trial results show that horizontal drainage boreholes have significantly improved longwall gas management, through controlling goaf gas pressure distribution and flow pattern. As a result, gas related longwall production delays were largely eliminated and the fugitive emissions from the mine were significantly reduced.

INTRODUCTION

Gas drainage in longwall mining in Australia is becoming increasingly challenging and complex with deeper mines, multi-seam environments beneath existing goafs, and surface environments where drilling conventional surface gas drainage wells is more constrained. Increased longwall retreat and development rates at a number of Australian coal regions, including the Hunter Valley, Illawarra and Bowen Basin have produced mine gas levels that are a serious threat to sustained and efficient coal production, and will potentially lead to increased fugitive emissions.

A step-change improvement in coal mine methane drainage strategies and technologies is required to effectively capture methane from the longwall goaf, surrounding seams and strata, before the methane enters the workings and ventilation system. Such an improvement will also enhance mining safety and remove one of the most significant barriers that constrain mining efficiency at Australian gassy mines now and in the future, particularly as mining depth increases.

A collaborative research project between the Glencore Bulga Underground Operations (hereafter referred to as "Bulga") and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been carried out, under the Australian Government Coal Mining Abatement Technology Support Package (CMATSP). The project aims to develop and demonstrate a holistic and optimal approach to planning, design and operational control of mine gas drainage to maximise methane capture and minimise fugitive emissions in gassy and multiple seam conditions. The project commenced in August 2013, and to date the major part of the work has been completed.

This paper presents the methodology and approach used and the innovative gas drainage system that resulted from the project.

DESIGN METHODOLOGIES AND PROCEDURES

A key objective of gas drainage design is to provide sufficient drainage capacity at optimally positioned drainage points that not only captures an optimal fraction of goaf gas emissions at an acceptable composition but also reduces methane emissions into ventilation (Guo et al., 2012 and 2014). To date,
the development and optimisation of a mine gas drainage design has been done largely by a trial-and-error method and has mostly proven to be inefficient and costly.

Gas emission during longwall mining is a dynamic process which involves interactions between mining induced coal and strata fracturing, de-stressing, de-watering, ventilation and gas drainage. Therefore, a clear understanding of the coupled strata, gas and underground water behaviours during longwall mining is crucial to determine key parameters from gas drainage design, such as gas emission source and emission patterns. An integrated approach consisting of site characterisation, field studies and numerical modelling was developed and carried out. The approach consists of four key aspects:

- site characterisation;
- integrated field studies;
- geomechanical and coupled numerical modelling; and
- Computational Fluid Dynamics (CFD) simulations.

Site conditions

The Blakefield South longwalls operate under old mine workings in highly gassy conditions and a multiple of seam environments. The working seam, Blakefield, dips at about 3 degrees and its depth of cover varies between 130 and 260 m. The seam comprises a number of plies with a total thickness ranging from 4.5 to 8.0 m. The extraction height ranges from 2.8 to 3.4 m. The LW3 panel, selected for field and numerical studies is 400 m wide (rib-to-rib) and about 3.5 km long. Figure 1 shows the mine layout, where LW3 is to be mined, and Figure 2 shows a stratigraphic section about LW3.

![Figure 1: Mine plan of Blakefield South mine. The panel with boreholes shown is the LW3 panel](image)

Some key observations from the site characterisation include:

- The overburden is highly banded, consisting of sandstone, conglomerate, siltstone, shale and tuff. No thick and competent layers such as sandstone overlie or underlie the mining seam within the depth of interest.
• No major geological structures such as faults and dykes that have a significant influence on gas reservoir conditions are present.

• The old Whybrow goafs, overlying around 70 m above the mining level, significantly influence goaf gas drainage performance. It is evident that a significant portion of the goaf gas drained by surface vertical wells was from the Whybrow goafs.

• The performance of surface vertical wells is not satisfactory in controlling goaf gas emissions, particularly in the initial 400 m from the longwall start-up. Frequent longwall production delays were experienced during the first 400 m retreat of LW2 and LW3 which totalled about two months.

• Some surface vertical wells to LW2 were operated for only a few days due to unacceptable high levels of oxygen in the drainage gas.

Figure 2: Stratigraphic section of the Blakefield South Mine

Integrated field studies of coupled strata, gas and water

The objective of these comprehensive and integrated field studies is to understand the coupled behaviour of strata, gas and groundwater during longwall mining. The studies cover overburden caving processes and strata movement, surface subsidence, surface vertical well stability, extent of mining influence, goaf gas pressure dynamics changes, gas flow patterns, gas content change before and after mining, and gas drainage performance under various operational parameters.

Key findings from the studies include:

• Mining induced fractures and delaminations extend up to the Redbank Creek seam quickly (in 36 m inbye the longwall face). Significant delaminations were observed in the interburden. This process indicates that gas would release rapidly from both overlying coal seams. Figure 3 shows the monitored overburden movement by one extensometer as an example.

• A piezometer, installed at a location 85 m away from the mining block, shows coal seam pore pressure decreases quickly between 50 m outbye and 100 m inbye of the longwall face. In the vertical direction, coal seams other than Woodlands Hill incur a significant decrease of pore fluid pressure.
• Surface goaf gas drainage borehole inspections with a borehole camera clearly show that the
goaf drainage boreholes were often blocked at levels higher than 30 m above the mining seam.
• The results indicate that longwall gas emission sources are the Redbank Creek and Wambo
seams in the roof and the Glen Munro seam in the floor, which is different to that predicted by
Flugge Model with Woodlands Hill seam being a significant emission source.

Figure 3: Monitored overburden movement above LW3

Geomechanical and coupled modelling studies

The objective of coupled numerical modelling is to extrapolate the field studies results into a 3D
dimensional space and provide key parameters for the consequent CFD simulations and the optimisation
of goaf gas drainage design. The shape and extent of the caved and fractured zones and the permeability
changes and distributions within these zones are assessed from the geomechanical modelling, which is
validated from field monitoring results. The coupled modelling is then further carried out to determine the
shapes of gas emission zones and various gas emission sources.

The numerical studies were carried out with a CSIRO developed computer code COSFLOW. Further
information about this code can be found in reference (Guo, et al., 2009). Figure 4 shows the 3D geometry
model constructed for the numerical modelling. Figure 5 shows the predicted de-stressing zone and the
permeability changes. Figure 5 also shows a result of the gas emission region at Wambo seam.

Figure 4: 3D geometry model used for COSFLOW modelling studies
CFD simulations of goaf gas drainage mechanisms and design optimisation

CFD modelling has been an important tool at CSIRO for studying goaf gas flows and optimising goaf gas drainage (Balusu, 2002). In this research, the CFD modelling is used to understand goaf gas flow patterns, gas drainage mechanisms with different means such as horizontal boreholes and vertical boreholes, and parametric studies for gas drainage optimisation. The results have clearly revealed drainage mechanisms under various means and provided valuable information to assist the optimisation of gas drainage design.

Figure 6 shows the CFD model constructed for the simulation of LW3. The parameters used in the model were based on field data including the ventilation rate, pressure difference across the longwall face, drainage parameters and gas emission rate. The model was calibrated by the methane concentration and flow rate in various surface goaf vertical wells as well as by current knowledge of goaf gas pressure distribution.

Taking the horizontal borehole drainage as an example, Figure 7 (a) shows the pressure contour on a vertical section 20 m behind the face. It is seen that sinks of low pressure are formed around the boreholes. Figure 7 (b) further shows that, under the low pressure sinks, gas is induced to flow towards the drainage boreholes away from the workings. These results illustrate that the horizontal drainage boreholes create low pressure sinks that protect the workings from goaf gas ingresses by changing goaf gas flow directions. Given the horizontal boreholes traverse along the direction of the longwall advance, the boreholes would provide continuous and consistent drainage mechanisms and capacity as the longwall advances. This system differs from using vertical boreholes which usually have varied drainage flow rate during mining.
DESIGN AND TRIAL OF A NEW GOAF GAS DRAINAGE SYSTEM

Design

The field and numerical studies provided a clear understanding of site conditions, technical issues with the mine’s surface vertical goaf wells, coupled behaviour of strata, gas and water, and gas emission sources. As a result, an innovative horizontal drainage was proposed and designed. The design is constructed on the basis of the following key principles and considerations:

- provide continuous and immediate capture of gas emissions before they reach the ventilation circuit;
- locate in the return side of the longwall to capture rich gas and maximise gas drainage efficiency;
- locate slightly above the caved zone to maintain borehole connection to the goaf and stability; and
- avoid drilling into any soft strata layers such as clay and coal seams.

A design of underground lateral boreholes was then made as shown in Figure 8. In the design, the lateral boreholes are drilled from underground to reduce the risk of borehole blockage and collapse. Five boreholes in the roof and five boreholes in the floor were included. The roof boreholes were located...
within 150 m of the ventilation return and vertically situated at a location between 13 to 20 m above the mining seam. The floor boreholes were designed to steer along the Glen Munro seam, with three boreholes located in the ventilation return side and two boreholes in the intake side. The floor boreholes aimed to reduce the Glen Munro seam gas flowing into the goaf.

Figure 8: Design of horizontal gas drainage system with underground lateral boreholes.
Drainage design implementation and monitoring management

The design was trialled at LW4 at its initial 400 m of retreat. The implemented borehole layout is shown in Figure 9 (a). The cross sections of the lateral boreholes are shown in Figure 9 (b) and (c), respectively. The two groups of roof and floor boreholes were each connected to a riser, drilled from the surface to a cut-through point. Each riser was 305 mm in diameter and connected to the goaf drainage plant situated on the ground surface to provide suction pressure to the underground lateral boreholes.

The configuration of these boreholes is summarised below:

- Five roof lateral boreholes were located within 105 m from the ventilation return roadway, with the nearest one 25 m from the longwall void edge. The spacing between every two boreholes was about 20 m.
- The roof boreholes were situated at 15-22 m above the mining seam, with the first one from the return the lowest.
- The horizontal section covered a distance of about 350 m.
- The roof boreholes were 145 mm in diameter, reamed from 96 mm.
- Five floor boreholes were drilled in the Glen Munro seam. Three were located close to the return side (26 m outside the LW4 panel to 105 m inside the LW4 panel), and two in the intake side (75 m of the maingate).
- The floor lateral boreholes were not reamed and were 96 mm in diameter.

Continuous monitoring of gas drainage performance was carried out. Both risers were equipped with a wellhead, which enabled continuous monitoring of suction pressure, drainage gas flow rate, gas composition, and operation parameters such as borehole opening percentage. Tube bundles were run down and connected to each of the roof lateral boreholes to monitor gas composition. Continuous monitoring of individual borehole flowrate was not enabled but manual readings were taken. In addition, a test of gas drainage performance with different operational parameters, such as various boreholes in operation and borehole opening percentage, were conducted.

Surface vertical wells were implemented in the remaining part of the LW4. There were also three surface vertical wells drilled within the trial area for a transition from horizontal drainage to vertical drainage. The first one, 4C, was located 240 m from the longwall start-up.

TRIAL RESULTS

Gas drainage performance

Roof lateral boreholes

Figure 10 (a) and (b) show the drainage flow rate and methane concentration in the first two months of LW4 operation, which covers both the underground lateral boreholes and the conventional surface vertical wells and compares the performance between the two means. It can be seen that:

- The roof lateral boreholes captured goaf gas with a continuous and consistent flow rate; while the vertical goaf wells gas flow rate fluctuated significantly.
- Methane concentration in the roof lateral boreholes was high and averaged 86%; while in the vertical wells, methane concentration averaged 68.3% and varied significantly.
- Methane concentration in the ventilation return was remarkably lower when the roof lateral boreholes were solely in operation (average 1.13 %) than that when goaf vertical wells were solely in operation (average 1.61%). This clearly shows that the roof lateral boreholes significantly reduced methane emissions from longwall operation into the ventilation circuit.
- Overall, in comparison to the goaf vertical wells, the roof lateral boreholes captured less gas but achieved a better result in controlling gas emissions into the ventilation circuit. When compared
to the surface vertical goaf wells, the roof lateral boreholes enabled gas to be captured from an area where it is more critical to goaf gas control.

(a) Layout of the trialled innovative goaf gas drainage system at LW4
(b) Cross-section along mining face

(c) Cross-section along mining direction

Figure 9: Implemented innovative gas drainage system at LW4 as a trial
Figure 10: Gas drainage performance of the innovative gas drainage system at the LW4 trial. (a) drainage flow rate; (b) drainage methane purity

Floor laterals boreholes

It is noted that the floor lateral boreholes in the Glen Munro seam were not connected to the goaf suction plant and the gas flow was driven by seam gas pressure only. No monitoring of flow rate and methane concentration was implemented for individual boreholes but the combined flow rate and gas composition was continuously monitored.

The floor lateral boreholes performed well with continuous and stable gas flow and consistently high methane purity (92%, the rest being mainly CO₂) before and during mining. The gas flow rate from the lateral boreholes was at about 400-450 l/s. A tracer gas test, where SF6 was injected into one of the floor boreholes, showed that no SF6 was captured in the ventilation circuit and drainage boreholes. This indicates the floor boreholes have effectively prevented Glen Munro seam gas from flowing up into the goaf and ventilation return.
Improvement of drainage efficiency and longwall coal production

Gas drainage efficiency has been used as a key factor to assess gas drainage performance and its effectiveness in controlling goaf gas emissions into the ventilation circuit. Gas drainage efficiency is calculated as a percentage of the drainage gas volume in the total gas emissions from mining operation. The gas drainage efficiency during the trial period was significantly improved and reached as high as 80%. The gas drainage efficiency fell again when the roof lateral boreholes were closed and only surface vertical wells were in operation. In comparison to the initial 200-300m of retreat at LW3, gas drainage efficiency in the trial period was increased from 14%-37% up to 80%. This clearly reflects that the underground lateral boreholes achieved significantly better results than the conventional surface vertical wells used at the mine, particularly in the initial mining stage.

Figure 11 (a) shows the recorded daily longwall production delays from the commencement of LW2 to LW4. Significant production delays were seen in the initial 2-3 months of mining operation at LW2 and LW3, where surface vertical wells were used to capture goaf gases. Conversely, in LW4 where underground lateral drainage boreholes were implemented, very limited delays were incurred.

The significant reduction of longwall delays, resulting from the improved gas drainage performance, led to a remarkable increase of coal production in the initial mining stage, as shown in Figure 11 (b). The LW4 coal production, in its first two months, was increased by 79% compared to LW3.

![Figure 11: Coal production delays caused by excessive gas emissions and coal production comparison in the first 2 months of LW2, LW3 and LW4](image)

Reduction of methane emissions to atmosphere

The trial results showed that, in addition to a significant increase in capture effectiveness with the underground lateral boreholes, the total specific gas emission was also significantly reduced for longwall operating in the same environment. This demonstrates that optimised gas drainage has reduced the raw emissions from the operation on top of increasing the abatement of emissions.

Applying the results achieved at the LW4 trial, an annual net reduction of 0.42 Mt CO2-e after drainage methane incineration could be achieved at the Blakefield South mine by adopting the drainage system trialled at LW4. This number is calculated based on LW3 gas emission data and an assumption of 315 mining operation days.
Another point worth highlighting is that the roof lateral boreholes in this particular Blakefield mining condition were analysed having no exposure to the Whybrow seam goaf gas. Gas bag samples show Whybrow goaf has a mix of about 58.8% CH₄, 36% N₂ and 5.2% CO₂. Excess N₂ level would have been seen if Whybrow goaf gases were also captured by means of gas drainage. High excess nitrogen levels are often seen in vertical goaf wells, however, no excessive N₂ level was seen in the underground roof lateral boreholes.

OUTCOMES AND IMPACTS

Following adoptions by Bulga

Following the successful trial at LW4, Blakefield South mine replaced the surface vertical goaf wells with underground lateral boreholes at the entire panel of LW5. The roof lateral boreholes were placed at similar locations to those at LW4, with four to five lateral boreholes intersecting the goaf during the LW retreat, as shown in Figure 12. However, a significant difference at LW5 compared to LW4 is that there were no floor lateral boreholes implemented at LW5. This difference provided a good opportunity to compare the two designs to further refine the gas drainage system for future applications.

LW5 has recently been completed. Roof lateral boreholes performed well at LW5 in capturing and controlling goaf gas and their effectiveness was similar to that of the trial at LW4. At the comparable initial mining stage, the average gas drainage flow rate and daily coal production at LW5 were 1252 l/s and 22,411 t, respectively, close to their counterparts at LW4 trial (1279 l/s and 23,121 t), and much better than that at LW3 where only vertical wells were used (1182 l/s and 13,806 t). A comparison between the LW3, LW4 trial and LW5 are shown in Table 1.

Table 1 Comparison of gas drainage and emission parameters at recent longwalls in Blakefield South mine

<table>
<thead>
<tr>
<th>LW</th>
<th>Retreat meter for comparison, m</th>
<th>Gas drainage method</th>
<th>Daily LW tones, t</th>
<th>Total gas* emission, l/s</th>
<th>Drainage gas flow rate, l/s</th>
<th>Ventilation gas flow rate, l/s</th>
<th>SGE, m³/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW3</td>
<td>35-223</td>
<td>Vertical</td>
<td>13,860</td>
<td>4004</td>
<td>1182</td>
<td>2822</td>
<td>25.7</td>
</tr>
<tr>
<td>LW4, Trial</td>
<td>30-259</td>
<td>Lateral (roof +floor)</td>
<td>23,121</td>
<td>2869</td>
<td>1702 (roof 1252, floor 423)</td>
<td>1167</td>
<td>10.7</td>
</tr>
<tr>
<td>LW5</td>
<td>30-220</td>
<td>Lateral (floor only)</td>
<td>22,411</td>
<td>3171</td>
<td>1252</td>
<td>1920</td>
<td>12.2</td>
</tr>
</tbody>
</table>

*Note: Gas include CO₂+CH₄
The consistent performance of the lateral boreholes at both LW5 and LW4 indicates that lateral boreholes are a reliable gas drainage method in such conditions as of the Blakefield South mine. In comparison to the gas drainage performance at LW3 and LW4, it has also been observed that the floor lateral boreholes in the Glen Munro seam in the LW4 trial would have made a significant contribution to controlling face and return gas levels.

The results enabled further refinement for gas drainage design for future wide applications, and have contributed to the design for the forthcoming LW7. Figure 13 shows the planned layout of LW7 goaf gas drainage lateral boreholes. It includes both roof lateral boreholes and floor lateral boreholes drilled into the Glen Munro seam. A number of floor lateral boreholes were also planned to be drilled into the lower Blakefield seam to prevent the predicted higher gas emissions in this panel compared to LW4 and LW5. To date, the borehole drilling has mostly been completed.

Figure 13: Horizontal goaf gas drainage plan at LW7. Red and Green – roof lateral boreholes; Blue – Blakefield working section holes; Pink – Lower Blakefield seam holes; Light blue – Glen Munro seam floor holes

Long term benefit from the innovative gas drainage system

According to the performance at LW4 and LW5, the innovative gas drainage system trialled at the Blakefield South mine has not only optimised methane drainage quantity and quality, but also significantly improved coal productivity and maximised methane emission abatement from mining operations. This result will deliver significant benefits to the mine in both the short and long terms. The project results have achieved the scheduled goals of this project.

The points below highlight the potential benefits the innovative gas drainage system can bring. The data are assessed on the basis of LW4 trial results.

- A net reduction of fugitive gas emissions to atmosphere of about 0.42 Mt CO2-e every year;
- An increase in methane capture and utilisation through drainage efficiency from 14-60% to around 80%, resulting in improved mining safety;
- An increase in productivity by 79% at the initial longwall mining stage through significantly reduced coal production delays; and
- An increase in efficiency delivering savings in excess of $10M per year.
CONCLUSIONS

Under the support of the Coal Mining Abatement Technology Support Package (CMATSP), a major collaboration research project between CSIRO and the Glencore Bulga Underground Operations was carried out at the Blakefield South mine. The project involves comprehensive studies covering site characterisation, integrated geotechnical and gas field monitoring and measurement, numerical modelling, and theoretical analysis. The studies have obtained many insights into the coupled strata, gas and groundwater behaviour in complex multi-seam longwall mining. These insights have resulted in a clear understanding of many factors that are critical to goaf gas drainage design, including the zone of mining influence, caving processes, gas emissions sources and emission patterns, and operational parameters. An optimal gas drainage system was therefore designed and trialled at the mine.

The trial demonstrated that the gas drainage system, which consists of a number of both roof lateral boreholes located 15-20 m above the mining seam and floor lateral boreholes in a floor gas sourcing seam, were very successful. The results showed a significant reduction in both ventilation methane level and drainage gas volume. Gas drainage efficiency was significantly improved from 14-60% to about 80% in comparison to the same section in the previously mined longwall, and gas related coal production delays were substantially reduced. As a result, coal production was increased by 79% in comparison to the same section in the previously mined longwall. It is estimated that with such a gas drainage system, the mine could reduce fugitive gas emission by 0.42 Mt CO2-e per year from its longwall operations. This innovative gas drainage system is now being used as the main goaf gas drainage method at the Blakefield South mine and has replaced the previous conventional surface goaf vertical wells system.

The project has successfully achieved the planned objectives to develop and demonstrate a holistic and optimal approach of planning, design and operational control to mine gas drainage, to maximise methane capture and to minimise fugitive emissions in gassy and multiple seam conditions. A wide adoption of this scientific approach will benefit Australia coal mines by improving mining safety, enhancing coal and methane production efficiency, and reducing fugitive methane emissions.

ACKNOWLEDGEMENTS

The authors are very grateful to the Australian Department of Industry and Science (the then Department of Resources, Energy and Tourism) for funding this research. The authors would also like to express their sincere gratitude for their significant contributions to the management and staff of both Glencore Bulga Underground Operations and CSIRO who have been involved in this project.

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