CFD Modelling of Goaf Gas Migration to Improve the Control of Spontaneous Combustion in Longwalls

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ABSTRACT

This paper provides an overview of computational fluid dynamics (CFD) modelling capability developed by CSIRO with the aim of improving the knowledge of flow migration dynamics within longwall goaf areas. The CFD models can be used to study the ingress of oxygen into the goaf in different ventilation scenarios and goaf drainage arrangements. This approach not only helps the design of effective gas control strategies but also the management of spontaneous combustion risk in the goaf. Innovative goaf inertisation strategies have been developed and implemented during longwall sealing operations. Work is continuing to develop general guidelines of proactive goaf inertisation strategies to suppress the development of spontaneous heating behind active longwall faces.

INTRODUCTION

Hazards resulting from the spontaneous heating of coal remain a major threat worldwide to the safety and productivity of underground coal mines. The most problematic situation may occur when spontaneous heatings develop in the presence of an inherently explosive atmosphere which may lead a local heating incident into an explosion hazard involving the entire mine working. In Australia lessons have been learnt from the tragic mine explosion at Moura No 2 underground mine with the loss of lives and the closure of the mine. Subsequent inquiries concluded that the explosion was initiated by spontaneous combustion. The seriousness of such incidents and associated financial loss was again highlighted by the recent closure of Southland Colliery due to the breakout of a spontaneous heating fire (Gallagher, 2004).

In addition to the intrinsic propensity of coals to self-heat, the occurrence of spontaneous heating within a longwall goaf is closely associated with the airflow characteristics behind the face. Air leakage occurs across the permeable goaf due to the existence of pressure differentials. The airflow pattern for level retreat and advance longwall faces has been widely studied, but little work reported on the details of airflow conditions in the goafs, particularly with inclined faces which are the common cases in reality. The use of inert gases such as nitrogen and boiler gas has become a preventive practice during longwall sealing operations in some mines. Current knowledge is still limited on the behaviour of inert gas in the goaf. Inert gas is often injected with little knowledge of where it is needed, or where it is going in the goaf. A detailed understanding of the flow patterns and distribution of gas flow in the goaf is necessary not only to improve the control of goaf gas emissions but also for spontaneous heating prevention strategies such as the injection of inert gas.

With the support of ACARP and JCOAL, CSIRO has been engaged in the investigation of gas flow migration dynamics within longwall goaf areas with the objective of improving gas capture, minimising the risk of spontaneous combustion and developing effective goaf inertisation strategies. A major component of this study is the development of computational fluid dynamics (CFD) models to simulate the various scenarios of ventilation arrangements, gas capture designs and inertisation strategies. This approach not only helps the design of innovative gas management strategies but also the control of spontaneous combustion risk in the goaf. Work is continuing to develop general guidelines of proactive goaf inertisation strategies to suppress the development of spontaneous heating behind longwall faces.

CFD MODELLING

CFD is commonly accepted as referring to the broad topic embracing mathematics and numerical solution, by computational methods, of the governing equations which describe the motion of fluid flow, the set of the Navier-Stokes equations, continuity and any additional conservation equations, such as energy or species concentrations. Today CFD has grown from a mathematical curiosity to become an essential tool in almost every branch of fluid dynamics, from aerospace propulsion to weather prediction. The availability of robust commercial CFD codes and high speed computing has lead to the increasing use of CFD for the solution of fluid engineering problems across all industrial sectors and the mining industry is no exception.

CFD modelling has been used in the minerals industries in a number of areas, including control of methane and spontaneous heating (Creedy and Clarke, 1992; Tauziede, Mouilleau and Bouet, 1993; Ren and Edwards, 2000), dust control (Aziz, Srinivasa and Baafi, 1993; Sullivan and Heerden, 1993), diesel particulate emissions (Currie, 1994), mine fires and explosions (Lee, 1994), auxiliary ventilation layouts in rapid heading development (Moloney, Hargreaves and Lowndes, 1998) and mineral processing (Fletcher *et al*, 1995). Although some of these studies are at their early stages, results from these investigations have shown the potential of CFD as a powerful tool in solving many problems in which gases or fluids move through or around objects in the minerals industries. More recently, CFD codes are being used in Australia for development of goaf gas control (Balusu *et al*, 2001) and goaf inertisation strategies (Balusu *et al*, 2002).

A commercial CFD code FLUENT has been selected for this study. FLUENT is a finite volume computational fluid dynamics code that solves the Navier-Stokes equations for both incompressible and compressible flows. An elementary calculation of transfers to and from the neighbouring volumes is performed for each surface of the mesh. These exchanges depend on the incoming and outgoing flows and on the intrinsic characteristics of the flow regions. A key feature of this code is its user-defined function capability, or UDF, which allows the user to develop stand-alone C programs that can be dynamically linked with the FLUENT solver to enhance the standard features of the code.

DEVELOPMENT OF LONGWALL GOAF GAS FLOW MODELS

Gas flow migration in a longwall goaf is complicated process as many factors are involved, such as ventilation layout and intensity, gas emission rate and compositions (eg the presence of methane and carbon dioxide), face (seam) orientation and dip, gas buoyancy and goaf permeability. A range of CFD models have been developed to achieve a detailed understanding of the gas flow mechanics and distribution in longwall goafs. In addition to innovative CFD modelling, the study also involved

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extensive validation and calibration of initial models using data obtained from field studies and parametric studies to investigate the effect of various parameters on goaf flow patterns. Models were then used in the development of gas and spontaneous heating control strategies through simulation of the effectiveness of various designs and control techniques. The CFD modelling work generally consists of a number of key stages, including:

- field studies to obtain the basic information on panel goaf geometries and other parameters;
- construction of 3D finite element model of the longwall goaf;
- setting up flow models and boundary conditions through UDFs;
- base case model simulations;
- model calibration and validation using field measured data; and
- extensive parametric studies and development of optimum strategies.

A key part of the CFD models is the incorporation of longwall goaf permeability distributions and gas emissions via a set of UDFs that are linked to the FLUENT solver. Flow through the goaf was handled using custom written subroutines, which were added to the 'flow through porous media' modules of the basic code. In these subroutines/modules, flow through the porous goaf regions was simulated by adding a momentum sink to the momentum equations. The sink had a viscous part proportional to the viscosity and an inertial component proportional to the kinetic energy of the gases. A number of subroutines were written to represent different ventilation and goaf gas emissions (gas drainage) scenarios, which were then combined with the main FLUENT program to carry out the simulations.

The distribution of goaf permeability was derived from results of extensive previous studies and longwall geomechanics models. Pressure, flow rate and gas distribution in a typical longwall goaf were used to calibrate the initial models and further refine the distribution of goaf permeability. Pressure, flow rate, gas concentration measurements and tracer gas study results in a typical longwall panel were used to further refine the distribution of permeability. A standard two-equation k-e model was used to estimate the turbulent transport through the flow region and the flow near the boundaries was approximated by the use of standard wall functions. The models were set up to simulate both turbulent flow conditions near the face and laminar flow inside the goaf region.

CFD longwall models can be developed according to the actual mine layouts, as shown in Figure 1, and hexahedral cells are commonly used as this enables greater accuracy of boundary layer calculations and the ability to stretch the blocks along roadways. The mesh used in the models was 'refined' with higher density mesh in the areas of interest such as areas next to the face and roadways. A typical geometry and mesh used in longwall goaf gas flow models is shown in Figure 2.

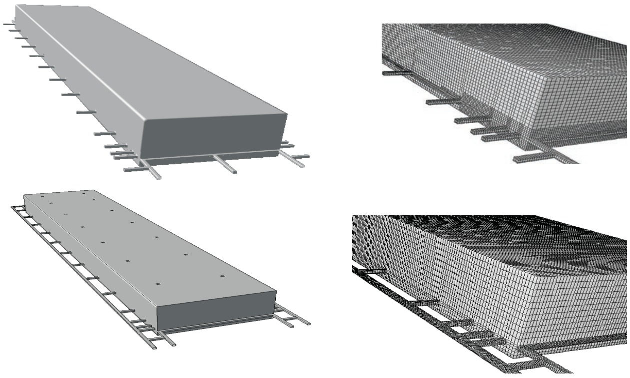


FIG 2 - Typical geometry and mesh used in CFD longwall goaf gas flow models.

LONGWALL PANEL VENTILATION STUDIES

The effects of poor mine ventilation are far-reaching and can result in problems with high gas emissions and spontaneous combustion. An analysis of face/panel ventilation systems would be useful to assess the potential of spontaneous heating and any changes in mining conditions or mine design which may lead to such hazards.

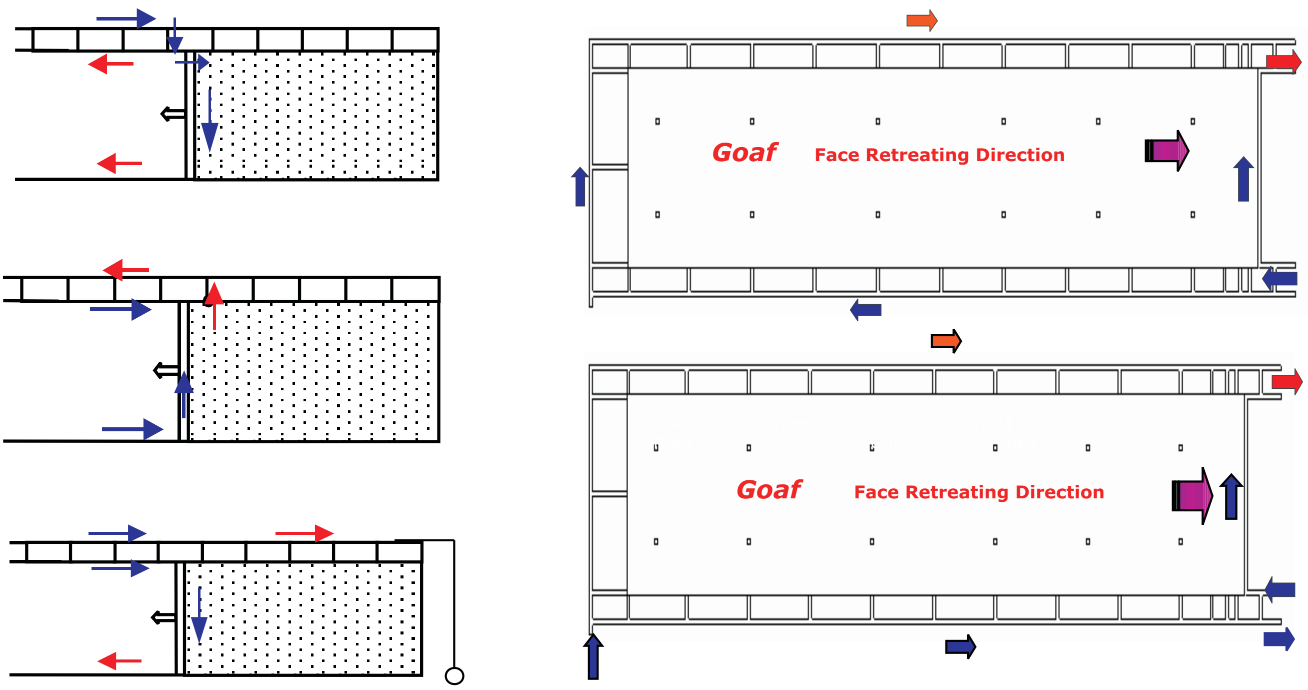


FIG 1 - A selection of longwall panel layouts (arrows showing the direction of ventilation).

A major feature of CFD modelling is its capability to predict what will happen under a given set of circumstances, ie it can answer many 'what if?' questions before a proposed design is implemented in the field. CFD models have been developed and used as investigative tools to provide preliminary prediction on goaf gas flow patterns based upon proposed ventilation arrangements, as well as an opinion on spontaneous combustion risk and optimum goaf gas drainage to help gas control in the face.

Figure 3 shows the application of CFD simulation in this area. The figure shows the oxygen distribution patterns under different panel layouts, face orientation and gas emission conditions. Information from these studies is useful in understanding the magnitude of oxygen ingress into the goaf areas and hence the potential for spontaneous heating under different ventilation designs. Such an understanding would be helpful in the selection of an optimum face ventilation designs that would not only allow the control of goaf gas emission but also the minimisation of spontaneous heating occurrence.

GOAF GAS CONTROL AND SPONCOM PREVENTION

A significant contribution from the CFD modelling work has been the development of innovative goaf gas control strategies in a highly gassy, Australian underground colliery with a propensity for spontaneous combustion.

The major factors that influenced spontaneous heating and CO production rates at the mine site included: ventilation design, seam structure/gradients, caving pattern behind the face, length of back return, location and orientation of faults/dykes, and condition of gateroads immediately behind the face. It was observed that although the effect of some of these geological factors on face control was minimal, they had a major influence on goaf gas flow dynamics and the occurrence of goaf heating.

CFD modelling was carried out to study the effect of the following parameters:

- open intake gateroad in the goaf on oxygen ingress,
- increased permeability due to dykes on gas flow dynamics,
- U ventilation system on gas distribution,
- 100 per cent CH_4 gas on goaf flow dynamics/buoyancy, and
- other goaf gas drainage optimisation studies.

An example of the effect of a partially open intake gateroad (simulating the effect of strong supports such as 'CANs') is shown in Figure 4. Results showed that an open intake gateroad in the goaf increases the oxygen penetration up to 300 to 400 m behind the face.

A particular application of CFD modelling has been the optimisation of surface goaf gas drainage designs with the objective to maximise the capture of goaf gas whilst minimising the risk of spontaneous combustion. Figure 5 shows the predicted oxygen ingress patterns into the goaf with different goaf gas drainage layouts.

Some of the innovative control strategies resulting from goaf gas control studies, which have a major impact on reducing spontaneous heating risk include:

- new goaf hole designs to ensure that oxygen concentration in the holes was below four to five per cent;
- goaf holes at 80 to 100 m away from fault/dyke areas;
- immediate sealing-off of the cut-throughs behind the face (only one cut-through open for back-return);
- reduction in air velocity on the intake side of the goaf;
- uniform and continuous operation of goaf holes (sudden peaks and lows in goaf drainage flow rate increases the sponcom risk).

These strategies, together with a set of guidelines for optimum goaf drainage strategies has been successfully implemented at several Australian coal mines, including Dartbook, Central and Appin, which will prove invaluable in helping other mines improve their strategies.

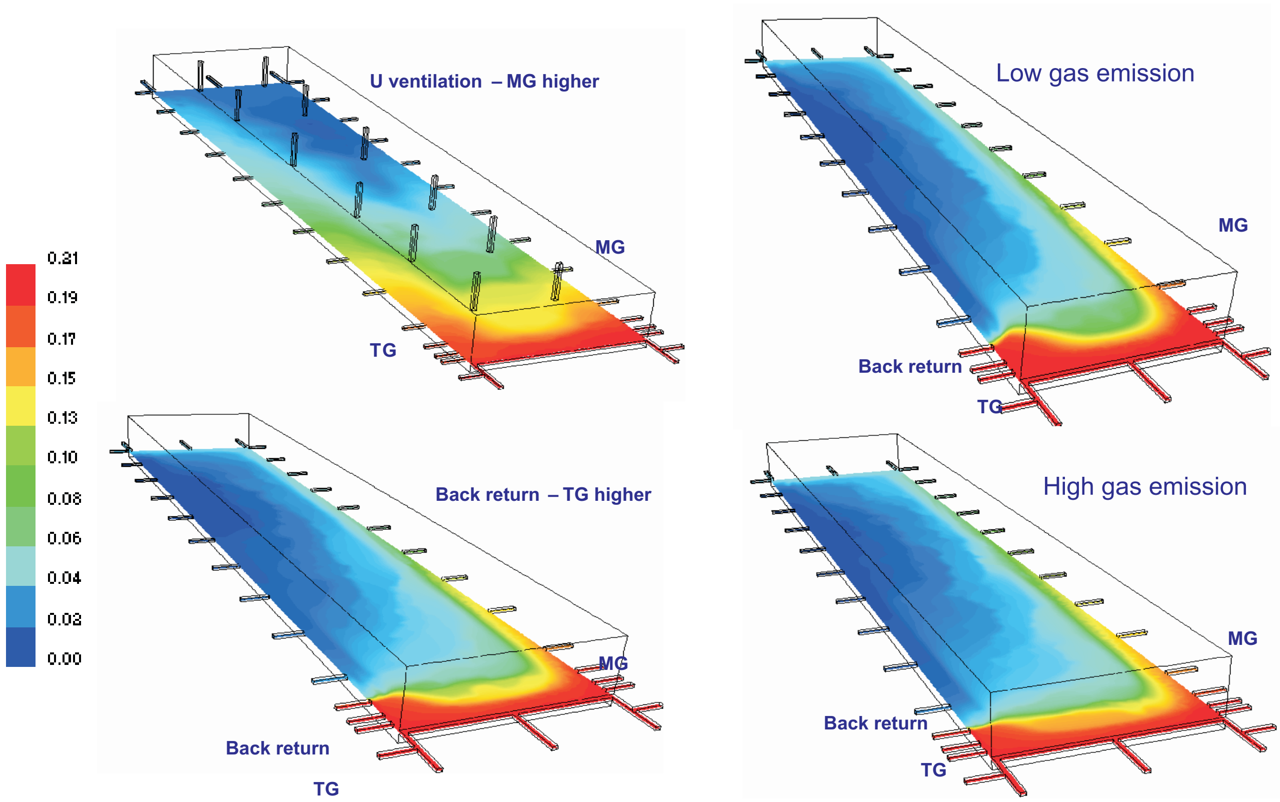
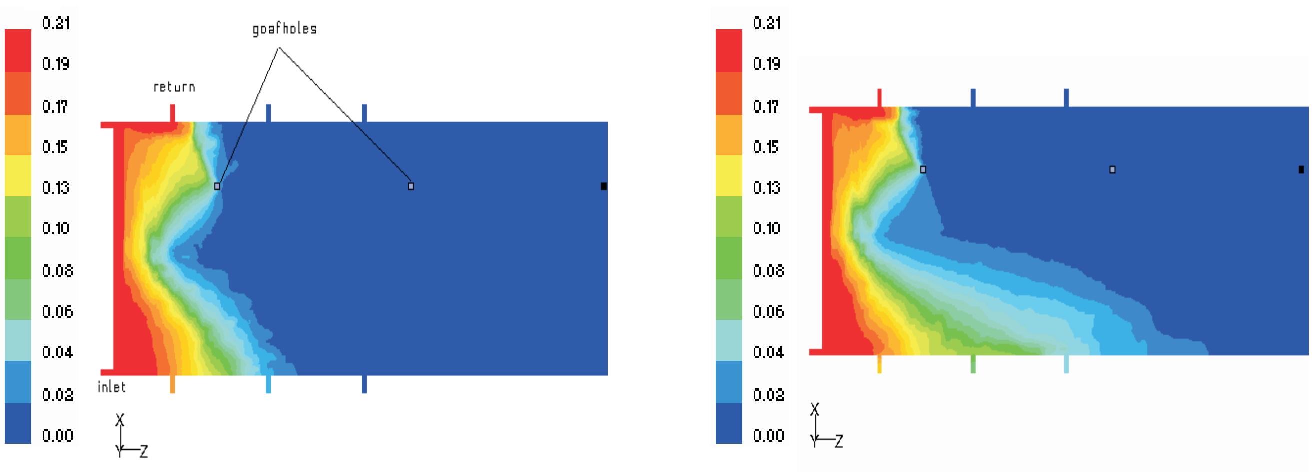


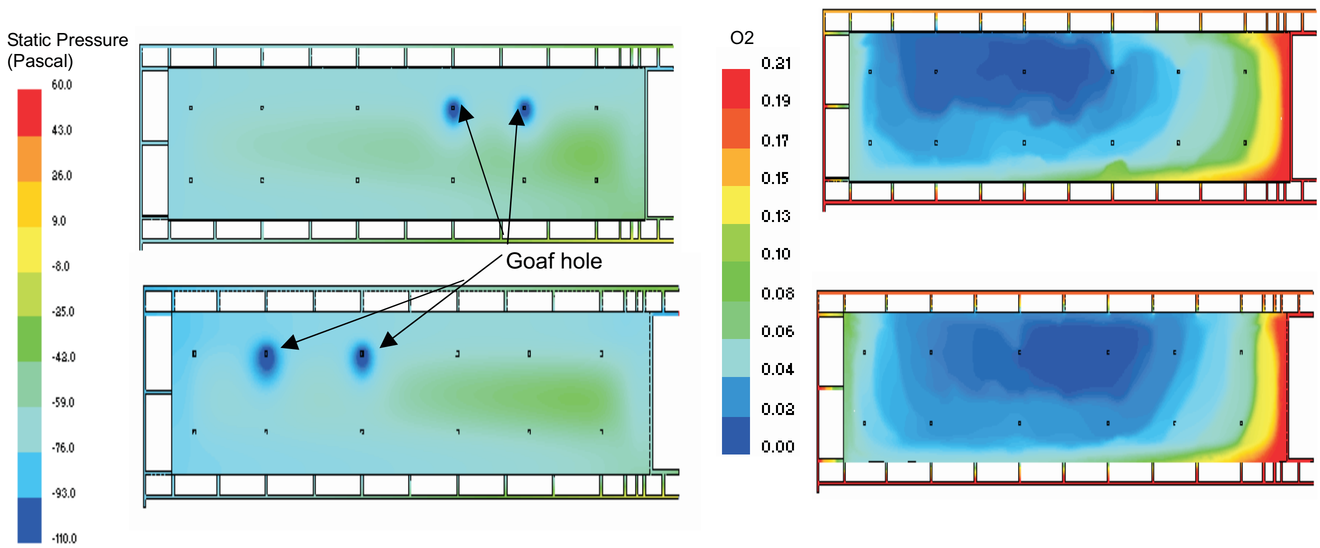
FIG 3 - CFD models for face ventilation layout studies – oxygen penetration into the goaf.



(a) Oxygen distribution – base case

(b) Oxygen distribution – open intake case

FIG 4 - Oxygen distributions in the goaf with partially open intake gateroad.



(a) Static goaf gas flow pressure

(b) Oxygen distribution

FIG 5 - CFD modelling of oxygen ingress into the goaf under different goaf drainage designs.

GOAF INERTISATION

In underground gassy coal mines it is generally recognised that immediately after sealing a longwall panel, the atmosphere behind the seals may enter and pass through the explosive range. The duration of explosive conditions in the sealed longwall goaf ranges from a few hours to one or two days or even a few weeks, depending on the gas emission rate and goaf characteristics. Therefore, any sealed area with methane as the seam gas has the potential to explode depending on the presence of ignition sources. To minimise this risk of explosions, the modern practice in some of the Australian mines is to inject inert gas into the sealed goafs immediately after sealing the panel. The specific objective of inert gas injection operations is to reduce the goaf oxygen levels below the safe limit of eight per cent (ie with a safety factor of 1.5 over the explosive nose limit of 12 per cent) before methane concentration reaches the lower explosive limit of five per cent.

Traditionally inertisation schemes usually involved just injecting inert gas through maingate (MG) or tailgate (TG) seals until goaf gas sampling results show that the oxygen level was below eight per cent. In many cases it was found that the goaf oxygen concentration was above 12 per cent even after two to three days of inert gas injection and in some cases an explosive atmosphere was also present in the goaf during inertisation.

CFD models have been used to develop optimum and effective strategies for inertisation during longwall sealing operations to achieve goaf inertisation within a few hours of sealing the panel. Again this study has combined the detailed analysis of the performance of various inertisation field trials together with CFD modelling results of different inertisation operations in order to develop the optimum inertisation strategies.

A number of parametric studies were conducted on the base case CFD models that had been calibrated and validated based on the information obtained from previous inertisation studies and goaf gas monitoring. These studies included changes in inert gas injection locations, inert gas flow rates, seam gradients, and different inertisation strategies to investigate their effect on goaf inertisation. Parametric studies were conducted under both steady state and transient conditions.

The modelling results show that there were no major differences in goaf gas distribution between the injection of boiler gas and nitrogen; however, different inert gas injection points resulted in entirely different goaf gas distribution. Figure 6 shows oxygen distribution in the goaf for inert gas injection at different locations after 24 hours of injection. Inert gas at a rate of 0.5 m^3/s was injected through the MG seal and at 200 m behind the face (through 3 c/t seal) on the maingate side respectively.

Analyses of the figures indicate that the strategy of inert gas injection through the MG seal was not as effective as the alternative strategy of inert gas injection at 200 m behind the face (ie through 3 c/t). Analysis of the various simulation results also indicated that longwall panel geometry, goaf characteristics, gateroad conditions in the goaf, goaf gas emission rates and composition, ventilation during panel sealing off period, chock withdrawal and panel sealing sequence would also have a significant influence on goaf gas distribution and inertisation.

The optimum inertisation strategies have been implemented at Newlands Colliery and were highly successful in converting the goaf environment into an inert atmosphere within a few hours of panel sealing.

PROACTIVE INERTISATION

'Prevention is better than cure'. On the basis of previous studies, an on-going project at CSIRO is the development and demonstration of proactive inertisation strategies with the objective to reduce the risk of spontaneous heatings in active longwall faces, in particular under unexpected scenarios such as during slow retreat/face stoppage due to difficult geological conditions. Figure 7 shows the steady state results of a preliminary CFD study of inert gas (boiler gas) injection at 10 m and 60 m on the maingate side respectively behind the face during 'normal' face retreat. The results indicate that inert gas injection at 60 m behind the face is more effective in narrowing the high oxygen zone thus reduce the risk of spontaneous heating. Further studies in this area are continuing.

CONCLUSIONS

In combination with field studies, CSIRO have conducted extensive CFD modelling work to investigate the gas flow mechanisms within longwall goafs. These studies have greatly improved the fundamental understanding of goaf gas flow patterns and gas distribution in the longwall goaf and thus help

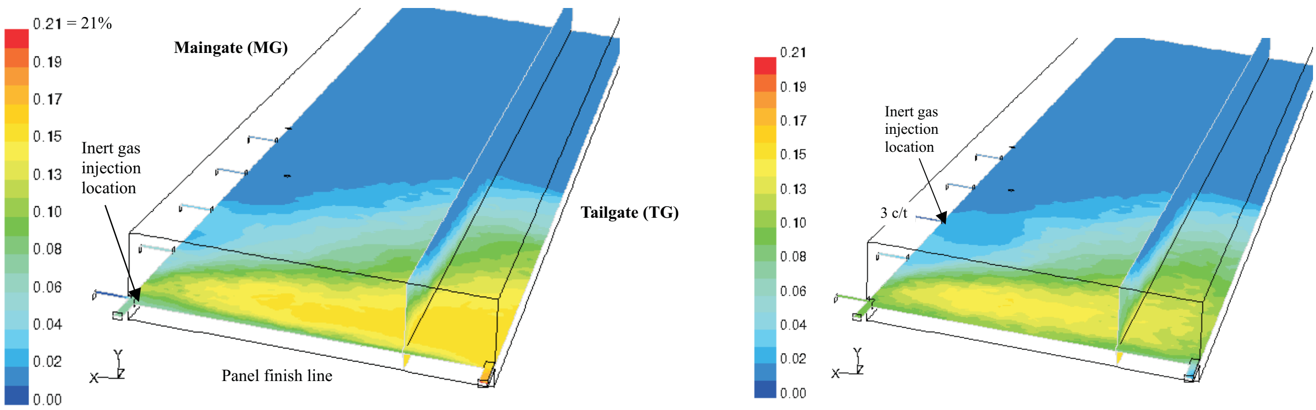


FIG 6 - Oxygen distribution in the goaf – with inert gas through MG seal and 3 c/t seal respectively.

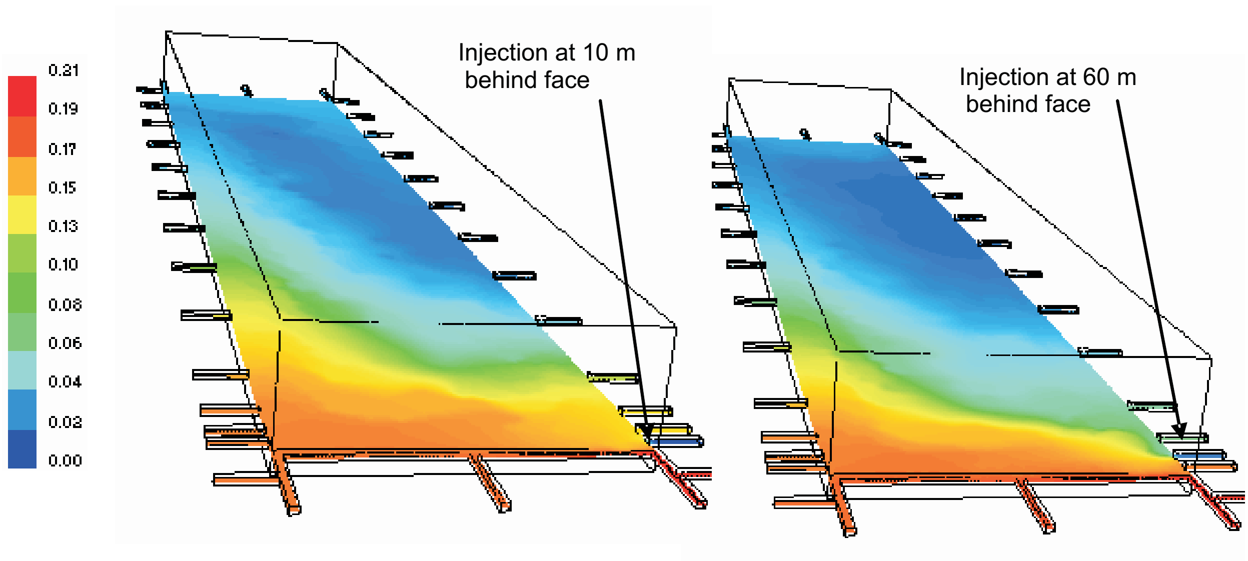


FIG 7 - CFD simulation of proactive goaf inertisation – oxygen distribution in the goaf.

the development of innovative gas control, spontaneous heating prevention and goaf inertisation strategies. Further investigations are continuing in a number of areas, including the study of proactive inertisation strategies to reduce the risk of heatings in the active longwall goafs.

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