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PROACTIVE STRATEGIES FOR PREVENTION AND CONTROL OF FIRES IN BORD AND PILLAR MINES WORKING IN THICK COAL SEAMS

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ABSTRACT: Coal fires associated with spontaneous combustion pose significant risks for underground mines. The hazard to the safety of the people working in mines, the loss of valuable coal reserves, the addition to fugitive Green House Gas (GHG) emissions and the huge costs involved in controlling the aftermath situations put these into one of the most critical parameters which have to be dealt with. Some of the research attempts taken to prevent and control coal mine fires and spontaneous combustion in thick seams worked with bord and pillar mining methods is presented.

A mine located in India which has a 22 year history of working a 10m thick coal seam with the blasting gallery (BG) technology for extraction of the pillars was selected for the study. The project investigated the geological, geotechnical, operational and ventilation parameters causing the frequent fire incidents. Several laboratories, desktop and modelling studies were made to give a better understanding of the contributing factors and develop strategies for the control of mine fires.

In the study computational fluid dynamics (CFD) modelling techniques were used to simulate and assess the effects of various mining methods, layouts, designs, and different operational and ventilation parameters on the flow of goaf gases in BG panels. A wide range of parametric studies were conducted to develop proactive strategies to control and prevent ingress of oxygen into the goaf area preventing spontaneous combustion and mine fires.

INTRODUCTION

Coal mine fire incidents increased significantly in recent years, as underground coal mining progressed towards extraction of thick seams, multiple seams and spontaneous combustion prone seams. Fires initiated by spontaneous combustion pose a major safety risk with the potential for explosion, but also can cause significant loss of coal reserves and contribute to considerable greenhouse gas emissions.

In Queensland about four high potential heating incidents occurred from 2004 to 2009 (Report by Qld mining inspectorate, 2010). In NSW mines about 16 self heating incidents are reported from 2005-2009 (NSW, Mine safety performance report, June 2010). Data from the United States reveal that more than 20 underground coal mines fires are due to spontaneous combustion occurred during the period from 1990 to 2006 (Trevits, *et al*., 2009). In china every year about 360 fire incidents are reported due to spontaneous cumbustion. In India it is estimated that 75 % of coal mine fires result from prolonged exposure of coal to atmospheric oxygen (Mohalik, *et al.*, 2009).The analysis of the various spontaneous combustion incidents in different countries, indicate that several factors like coal left in the goaf area, slower rate of extraction, presence of geological disturbances, method of mining, ventilation practices and coal characteristics are the main cause of mine fires and heatings (Balusu, *et al*., 2005)

Working thick seams with bord and pillar technologies is a regular practice in Indian Coal mines. A French blasting gallery (BG) technology; (a thick seam mining method) was introduced in 1988 in several mines of The Singareni Collieries Company limited (SCCL); a government owned coal mining company in India. In one of the mines where the BG method is deployed there were repeated incidents of heating and fires with spontaneous combustion. About 60% of the BG panels are closed prematurely after extraction of 55-60% of coal (SCCL, internal report, 2007). The study explained in this paper aimed at developing control strategies for prevention and control of fires due to spontaneous combustion at this coal mine. The work taken up though includes field characterisation, laboratory investigations, field monitoring and design of proactive fire control strategies, here more emphasis is given on the gas flow modelling studies. The study also investigated the impact of different mining designs, methods and ventilation systems on spontaneous combustion events and developed appropriate proactive control strategies.

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OVERVIEW OF THE BLASTING GALLERY (BG) MINING METHOD AND FIRE ISSUES

The Blasting gallery (BG) technology was first introduced at Godavari Khani-10 Incline (GDK10 Colliery) of the Singareni Collieries Company Limited and subsequently followed at other mines of SCCL. The method was introduced in SCCL mines because of the advantage of a high percentage of extraction and its suitability for use in thick seams.

The working of the BG method involves development of rectangular stooks in the bottom section of the coal seam. The stooks are extracted by drilling and blasting of long holes up to the full thickness (10m) of the coal seam. Remotely operated electro hydraulic tyre mounted load haul dumpers of 3 m^3 capacity load the blasted coal and discharge onto a chain conveyor with inbuilt lump breakers in the outbye level or the rise gallery. During development, the galleries are supported by roof bolts. While extracting the pillars the galleries are additionally supported by rolled steel joists placed over a pair of 40 T open circuit (OC) hydraulic props.

About 22 BG panels were worked at the mine in three areas separated by faults. During the initial years the BG panels are worked without fire issues in shallow depth areas. When the workings were shifted to deeper regions incidents of heatings and fires due to spontaneous combustion significantly increased. Some of the panels were worked only for 5 months before encountering spontaneous combustion problem. To summarise, the mine experienced fires in 60% of the BG panels leading to pre-closure after extraction of 55-85 % of the area of the panels.

Attempts are made to control the fires in BG panels by following some traditional inertisation practices like flushing with nitrogen and CO_2. In some cases foam technologies and fire sealants are also used. On a review of the past fire instances it is understood that though inertisation attempts were made in both sealed off panels and the working panels but the success rate varied widely. Some panels were sealed off early even following inertisation techniques, whereas some panels worked with limited success. A critical assessment of past fire incidents and inertisation attempts revealed that:

- The spontaneous combustion issues in BG panels are increasing with increase in depth of mining, associated with the changes in panel design such as larger pillars and stooks;
- Ventilation factors such as sluggish air flow in the goaf areas and leakages between the panels and high pressure differentials have contributed to development of spontaneous combustion;
- Geotechnical factors such as strong roof and associated caving difficulties, thick seam extraction, crushing of stooks in the panel and crushing of barrier pillars between the panels contributed to the development of spontaneous combustion;
- Coal left in the floor of the working section and loose coal left in the goaf due to larger stooks have contributed for spontaneous combustion; and
- Traditional inertisation practices such as inert gas injection at the top level in the panel at very low flow rates are found to be ineffective in controlling spontaneous combustion in BG panels.

DEVELOPMENT OF COMPUTATIONAL FLUID DYNAMICS (CFD) MODELS AND PARAMETRIC STUDIES

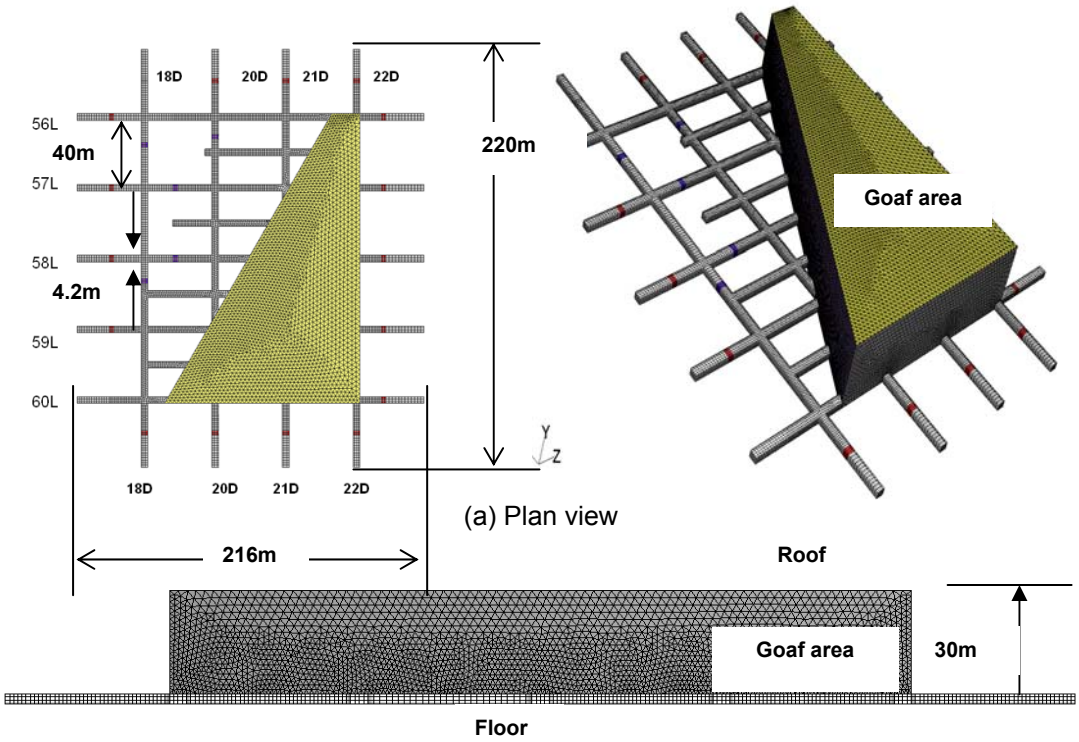
Simulating the ventilation and goaf gas behaviour with different parametric conditions that exist in the field with the help of computational fluid dynamics (CFD) techniques is already being practised for Australian mine conditions. Similar CFD studies for air flow patterns in BG panels are conducted for a better design of inertisation strategies. The main objectives of the CFD modelling are:

- To identify air flow patterns in the goaf areas of BG panels with different ventilation systems;
- To investigate the inert gas flow patterns in the goaf areas with different inert gases, injection point(s) and flow rate(s);
- To carry out extensive parametric studies on variations in ventilation flow rates, panel design parameters, operational parameters, and
- To identify and develop the most effective strategies for control of spontaneous combustion and mine fires.

Modelling is carried out using "FLUENT", a CFD code that solves the finite volume Navier Stokes equations. Initially the base model is set up to simulate gas flow in the BG panel working and goaf atmosphere. The boundary conditions for the simulations are assumed based on field observation data, geo-mechanical studies and historic data. Figure 1 shows the CFD model geometry for the BG panel with dimensions of the model. The main parameters for the base model are as follows:

- 3D BG panel with a dimension of 216 m (panel length) X 220 m (panel width) X 30m (Goaf height above roof);
- There are 9 rooms for the extraction operations;
- The panel is extracted up to an area of about 9000 m^2;
- The height and width of the roadway are 2.8 m and 4.2 m respectively.

A key part of the CFD model is the incorporation of BG panel goaf permeability distributions and goaf gas emission via a user defined function (UDF) linked to the CFD solver. The intake and return of the BG panel are defined as velocity inlet or outlet boundary conditions with other seals and solid pillars as walls in the model. Several other factors like diluting the blasting fumes, dust control and control of face temperature and humidity are also considered before finalising the base case CFD model for conducting different parametric studies. In the base CFD models several simulations are studied with options like, single and multipoint inert gas injection, variations on inertisation by changing the inert gas flow rates, effect of type of inert gas used and effect of sealing the bottom on inertisation.

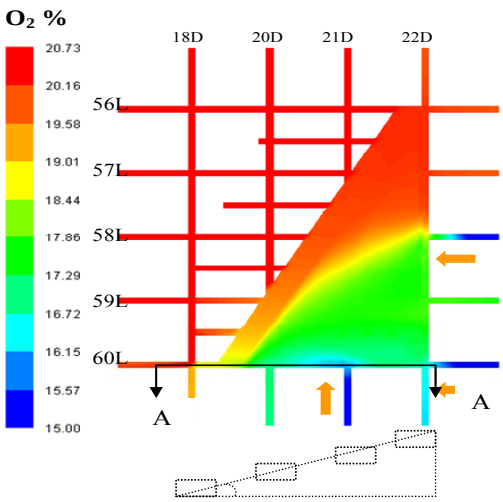


(a) Plan view

(b) 3D view from panel start-line

Figure 1 - CFD model geometry and mesh for the BG panel

Studies revealed that effective inertisation is achieved with three optimum inertisation injection points which are located inbye near to the start line along the dip and the bottom level. The inert gas flow rates of about 20 L/s from each point is found to be the optimum quantity for effective inertisation. Better inertisation effects are observed when CO_2 is used as inert gas compared to N_2 and boiler gas. The CFD model with the optimum inertisation pattern used for parametric studies is furnished in Figure 2.



Section A-A; BG Panel worked down dip at 1.28^0

Inert gas -Carbon dioxide = 20 l/s at each point

Figure 2 - Inertisation results with CO2 at 3 locations

In the BG working system the bottom levels are extracted first and are sealed off periodically from the lower level to higher level in ascending order before the completion of the panel. Several CFD simulations are carried out for finding the pattern of inertisation when the bottom most levels are sealed off. The results indicated that effective and improved goaf inertisation is achieved by sealing off the two bottom most levels of the BG panel.

Several parametric studies are conducted to study the effects of ventilation flow rates, face orientations and, methane emission rates on the inertisation pattern. With respect to the quantity of gas flow in BG panels the CFD results indicate that there is no marked difference in the inertisation pattern at the bottom levels of the BG panel when the ventilation flow is either halved or doubled. But it is observed that, the lower the air intake rate, the better is the performance of inertisation. The studies conducted on the effect of panel orientation indicated that the buoyancy effect is not significant as the chosen inclination of 1.28^0 is small. Only minor differences are observed when the BG panel is dipping inbye where the inertisation at the start line and bottom levels is found to be marginally more effective. The study simulations on the amount of methane gas released in the BG panels indicated that the variation in gas emission rates has no significant effect on inertisation.

DEVELOPMENT OF PROACTIVE FIRE CONTROL AND PREVENTION STRATEGIES

From the results of CFD modelling and extensive parametric studies the following important parameters are considered for designing the optimum strategies for control of spontaneous combustion and fires in BG panels:

- design of ventilation system for working BG panels;
- establishing a comprehensive gas monitoring system;
- conducting induced blasting for proper caving of the BG panel goaf ; and
- inertisation and sealing practices while working BG panels.

From the results of the initial field trials and the extensive CFD modelling with parametric studies it is considered that choosing the appropriate ventilation system will be one of the most important factors for control of mine fires. CFD models are used for simulating the effect of different ventilation systems on the goaf gas flows in the BG panels. Figure 3 shows the oxygen concentration patterns at the working seam level for BG panels with descentional and ascentional systems respectively. Modelling results indicated that ascentional ventilation allows air flow to migrate through much of the goaf area and therefore provides good flushing and cooling effects to the goaf; on the other hand, descentional ventilation has less goaf airflow flush and therefore offers advantages for goaf inertisation. It is considered better to follow the descentional ventilation in the BG panels for control of spontaneous combustion.

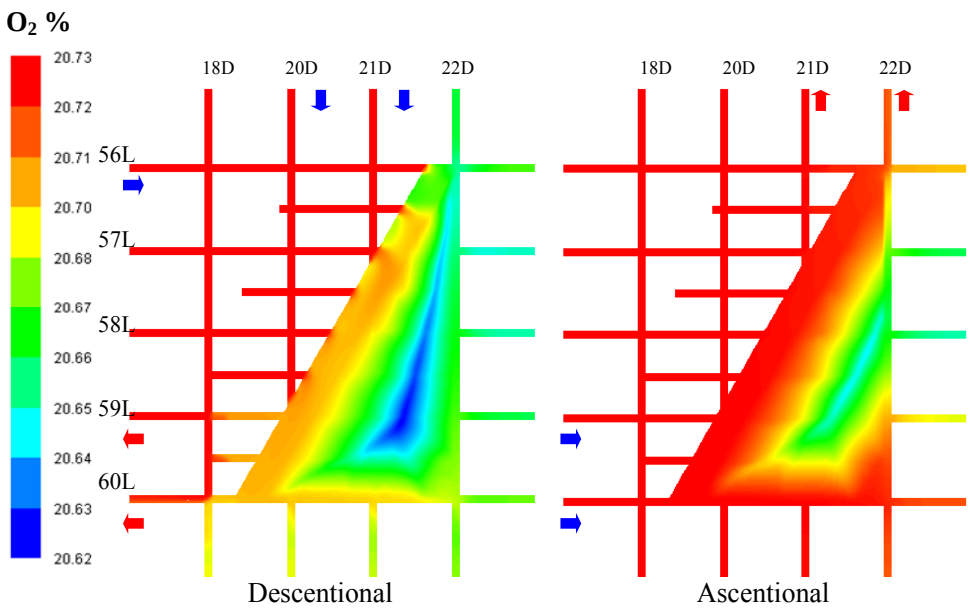


Figure 3 - CFD model for descentional and ascentional ventilation systems in BG panels

In the earlier BG panels, CO concentration in the return air is used as an indicator for detecting the development of spontaneous combustion. In most of the previous fire incidents the CO levels in the return air have increased more rapidly from almost nil values to about 300 ppm within a very short span indicating that the heating is in an advanced stage leading to premature sealing off the BG panels. The system of collecting the samples and the analysis methods are found to be unsuccessful in detecting the very low values of the spontaneous combustion indicator gases during the initial stages of heating.

Permanent steel pipes are installed in the working BG panels and sealed off BG panels for the dual purpose of injecting the inert gas to the required locations in the goaf and also to draw the goaf gas samples into the bags for further analysis. The sampling system is improved by way of drawing the samples into gas bags using a suction pump arrangement. The samples are analysed with gas chromatographs for the concentration of the goaf gases viz., CO, CO_2, CH_4, H_2, O_2 and N_2. The low level concentrations of CO and hydrogen (about 10 ppm levels) obtained from gas chromatograph analysis results are used as indicators for determining the early signs of heating in the goaf of BG panels.

In the BG system of mining the caving pattern of the roof strata into the goaf after the extraction of thick coal seam played an important role in contributing to the occurrence of fires. Good caving of the roof strata into the goaf area created a barrier for the ingress of oxygen into the goaf. In the new field strategy induced blasting practice is carried out more effectively for every 5 m of stook retreat with depth of the blast hole up to 10 m.

From the CFD simulation results the behaviour of the goaf gas flow is identified. The parametric studies with CFD models are conducted with several options like varying the ventilation, gas emission rates, inertisation points and quantities and change in operating conditions. The simulations helped to a better understanding of goaf gas flow pattern and helped choose the various options available for developing of most effective fire control strategies in BG panels. The results indicated that introduction of good inertisation practices is essential for preventing the spontaneous combustion and fires in BG panels. The inertisation pattern chosen for the BG panel is shown in Figure 4.

Based on the simulation results the following optimum strategies are implemented at the field site to control spontaneous cumbustion incidents and mine fires in BG panels:

- BG panel is ventilated with descentional system with a quantity of 2200 m^3/min to 2800 m^3/min for adequate comfort levels at workings and for effective heat dissipation.
- Periodic and frequent induced blasting is carried out in BG panel galleries for uniform caving of goaf and good packing of goaf area.
- Permanent steel pipes are installed for inert gas injection and goaf gas monitoring in BG panel.

- Inertisation attempts are initiated after 2-3 months of panel retreat with a flushing rate of 3-4 T/day for a period of 3-4 months at two to three points located most inbye in the bottom most levels.
- CO_2 is used as inert gas for the working panel and nitrogen in the neighbouring sealed off panels.
- Bottom most levels are sealed immediately after completion of coal extraction at outbye location and inert gas injection is increased to 8-10 T/day with more inertisation points.

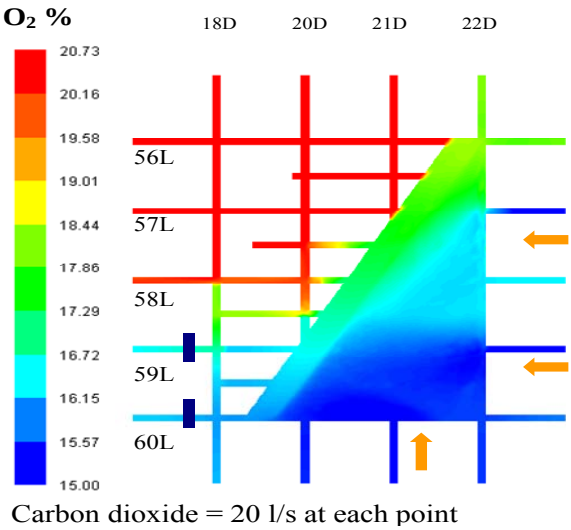


Figure 4 - Inertisation strategy adapted by injecting CO_2 at three locations after sealing off two bottom levels

RESULTS

The induced blasting has resulted in regular caving and compaction of the goaf and controlled ingress of air. Injected inert gas into goaf is retained well and created a good inert atmosphere. Figure 5 depicts the sustained levels of CO_2 in the goaf area which is obviously due to better compaction of goaf by way of efforts made in the form of junction blasting in lower levels and induced blasting in all working levels.

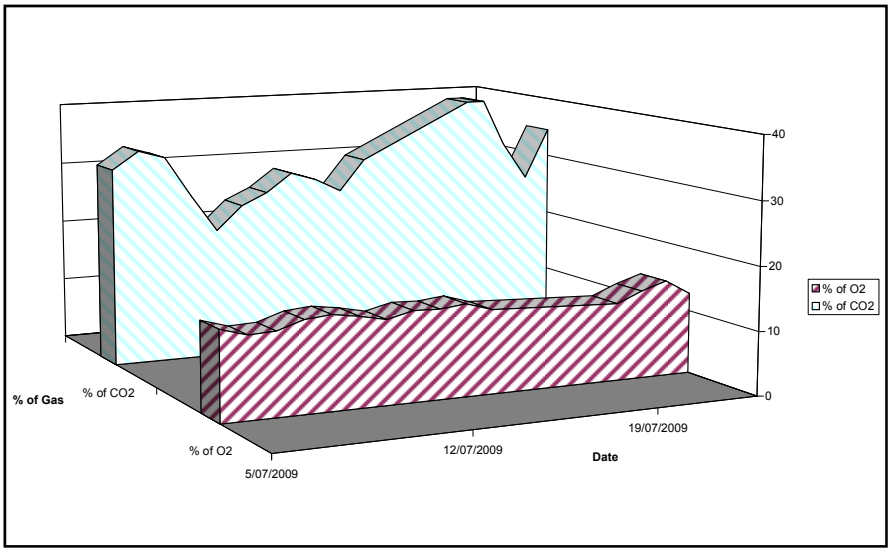


Figure 5 - Trend of goaf gases showing the effect of induced blasting

Observation of variations of spontaneous combustion indicator gases shown in Figure 6 found that there is no increase in either CO or H_2 with the normal laboratory monitoring. But when the samples are analysed with a chromatograph the presence of considerable concentrations of CO and H_2 are observed. The improved goaf gas sample collection and analysis helped in detecting very low levels of coal oxidation gases at an early stage of heating due to spontaneous combustion.

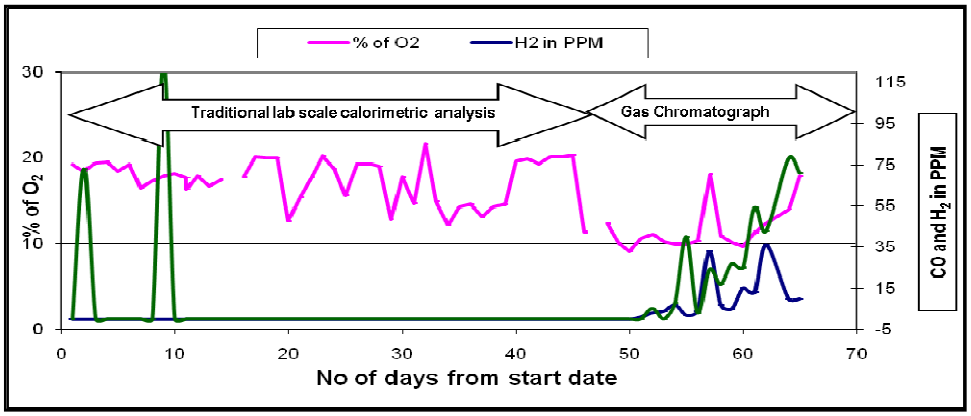


Figure 6 - Variation in goaf gases by method of analysis

During the implementation of field trials the bottom two levels were sealed off at three months and four months respectively after completion of coal extraction from these levels in the BG panel. The results of goaf gas monitoring at one of the bottom level after sealing is furnished in Figure 7. Observation of the goaf gas trends at these points indicated that CO_2 is found to be increasing by up to 50% and the oxygen levels are stabilised below 10% immediately after sealing off the levels. It is also seen from CO and hydrogen levels that coal oxidation is under control.

The results of the various strategies followed for control of fires and heatings due to spontaneous combustion are analysed in different stages during the total working period of the BG panel. During the initial three months of the panel the goaf atmosphere is in the formation stage and high levels of oxygen are observed in the goaf. Inertisation started at the lower level after two months of panel start. The CO_2 levels are found building up in the lower levels but not reaching the upper levels till three months period.

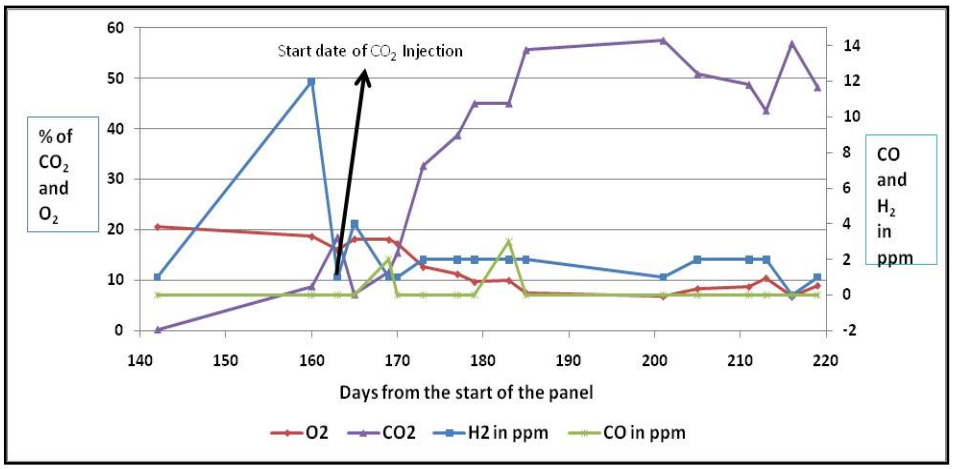


Figure 7 - Goaf gas trend when bottom level sealed off after 5 months with full inertisation

During the period of three to six months inertisation was started from two more points. The monitoring results during this period show that at the lower most level CO_2 levels reached up to 45-50% after 5 months and stabilised. It is also seen that though after 5 months the oxidation products of coal i.e., CO and hydrogen showed some increased trend for a few days at the lower most level but are immediately brought under control due to effective inertisation. In contrast to the results at the lower levels, the CO_2 build up is slow in upper levels and gradually reached up to 40% by the end of 6 months. There is no indication of increased oxidation of coal as CO and hydrogen levels at all the monitoring points are found to be below 10 ppm.

During the last stages of six to eight months of the panel the results show that the goaf inertisation is effective with the CO_2 levels stabilising at 40% and oxygen levels at 10-12% throughout the entire goaf area of the BG panel. The CO and hydrogen levels are found to be below 5ppm indicating no incidence of spontaneous combustion and fire in the BG panel. A snap shot of the range of the gas levels at the lower most level from the start till the end of the BG panel is furnished in Figure 8.

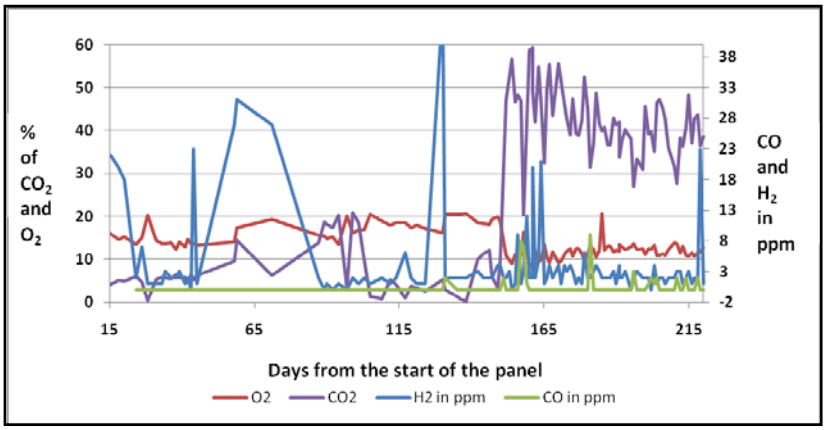


Figure 8 - Goaf gas levele in lower most level from start till end of the BG panel

CONCLUSIONS

Increasing the frequency of induced blasting, initiation of goaf breakage at the start line and additional blasting at the lower level junctions are found to be effective for regular and good caving of goaf which resulted in better compaction of goaf. Sealing off the bottom levels quickly has contributed to better retention of injected inert gas in the goaf area. Both these factors have contributed to the preventing the occurrence of fires throughout the working of BG panel.

Introduction of advanced gas monitoring system helped in assessing the behaviour of O_2, CO_2, CO and H_2 in the goaf quickly. On detection of changed behaviour of goaf gases spot actions like increasing the inert gas injection and modifying the ventilation quantities are initiated for controlling the ingress of oxygen into the goaf.

Inertisation is found to be most effective strategy which has contributed to the control of spontaneous combustion in BG panels. The CFD models and parametric studies helped in identifying correct locations and the optimum quantity of inert gas required for prevention of fires in BG panel.

The various strategies implemented during the field trials are found to be effective and successful as the BG panel was worked safely and sealed off without any incidents of spontaneous combustion after 8 months from the start. It is to be noted that in earlier times most of the panels were closed without complete extraction of coal in five to seven months period.

Field trials demonstrated that risks of spontaneous combustion and mine fires are reduced considerably in the BG panels which could lead to continuation of the BG technology in the future for working thick coal seams. The study improved the safety status of the BG workings considerably which directly contributed to the better extraction of coal from the panel. Overall benefit to the coal industry is observed by way of improvement in safety, and increase in production and productivity.

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