2012

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Publication Details
X. Choi, Application of a numerical model for outburst prediction, control and management, 12th Coal Operators' Conference & The Australasian Institute of Mining and Metallurgy, 2012, 286-293.

APPLICATION OF A NUMERICAL MODEL FOR OUTBURST PREDICTION, CONTROL AND MANAGEMENT

Xavier S. K. Choi

ABSTRACT: The basic underlying mechanism for outburst initiation involves the expulsion of coal at a pressure gradient above a critical value which is directly related to the strength and porosity of the coal at the current state, and the composition (degree of gas saturation) of the pore fluid. Coal strength, porosity, stress, gas pressure and pressure gradient are important for outburst initiation. Permeability and rate of desorption can be important for outburst evolution by controlling the amount of gas that would become available to drive an outburst. The severity of an outburst depends on gas pressure, the hydrodynamic force, the strength and toughness of the coal, and the amount of free gas that becomes available during an outburst. For the same pressure gradient, the degree of violence is greater for weaker and more friable coal. Outburst propensity can be reduced by changing the method of mining, mine geometry, and the preventive and control measures adopted by the mines.

The relative importance of the various factors and parameters will depend on the conditions of individual mines. As the interaction among the various processes and factors leading to outburst can be very complex, it is necessary to treat the coal-rock-stress-structure-gas interaction as a system. For outburst prediction, one approach is to use a numerical model that can model the individual processes and their interactions. This paper lists some of conclusions that have been derived from the results of the laboratory experiments and the modelling studies conducted to date and describes how the model can be used to help a particular mine assess outburst proneness and the potential risks, and to identify the critical factors for the purpose of outburst control and management. Based on the assessed risk and the degree of uncertainty, one may choose complete prevention or suitable control and management measures, without undermining safety which is one of the most important considerations.

INTRODUCTION

An outburst is a mechanical process which involves the transport of coal, and possibly also some rocks from the adjacent strata, which have failed due to tectonic history or mining induced stress redistribution. The outburst coal is expelled by free gas which is under pressure and which can generate enough force to mobilise and transport the coal. The speed at which the coal is expelled depends on the size of the fragmented coal, the amount of potential energy in the gas, and the drag and pressure forces generated by the gas on the coal. Even though outbursts can be broadly defined as dynamic events involving the instantaneous expulsion of coal and gas in underground coal mines, each outburst may occur under different sets of conditions, with different manifestations.

A lot of research on outbursts has been conducted both in Australia and overseas over many decades. It has been suggested that the main factors for outburst initiation are stress, strength, gas pressure gradient and the amount of gas that is available to drive an outburst (Briggs, 1921; Ruff, 1930). The parameters which have been used for outburst prediction include strength, fracture toughness (or energy required to form new fracture surfaces), reservoir pressure, gas content, rate of gas desorption, porosity, and geological structures.

Various indices have been developed and used for outburst prediction by incorporating some of the factors and parameters mentioned above. However, as suggested by Lama (1995), all the methods based on some parameters or indices for outburst prediction "can be used for defining the proneness of a seam or a part of the seam prior to mining, but this is only a descriptive method and does not help in forecasting an outburst condition." A specific set of parametric or indicial values may work well for a particular mine, but it may not work for a different mine because of operational issues or different in situ conditions. It is therefore not unusual that the adopted values are sometimes adjusted for different mines (Black, *et al.*, 2009; Liu, *et al.*, 2011).

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Based on the work of Ripu Lama, the Outburst Mining Guideline: MDG 1004, prepared by the Outburst Guideline Committee of the Department of Mineral Resources of New South Wales in 1995, requires that for mines mining the Bulli seam, normal mining can only proceed if the gas in the barrier region around the mine opening has been drained to below the gas content Threshold Limit Values (THV's). The THV's depend on gas composition and THV's of 6.4 m^3/t and 9.4 m^3/t for 100% CO_2 and CH_4 respectively were suggested by Lama (1995). The THV's have later been revised slightly for some mines. The approach based on gas content thresholds has worked well, with a few exceptions, in preventing outbursts in Australia since its introduction. Pre-mining gas drainage is also a common practice in Poland, China and Russia for controlling outbursts (Lama and Saghafi, 2002). In China, gas pressure instead of gas content threshold value is used in some of the mines as one of the indices for outburst control. In one of the mines, tectonically undisturbed it was considered safe to mine if gas content less than 12 m^3/t (most of seam gas in the Chinese mines has a high methane composition). This coincides with Lama's (1995) suggested THV for mining in a 100% CH_4 environment in the absence of structures. However, in some areas of the mine, based on the sorption properties of the coal, "when gas content is lower than 12 m^3/t, the coal seam will not be outburst prone at all, when gas content falls in the range of 12 to 20 m^3/t, the coal seam should be managed as a outburst threatened area and when gas content is higher than 20 m^3/t, the coal seam will be determined as having outburst potential (Liu, *et al*., 2011)." Based on a gas pressure threshold value of 0.74 MPa for tectonically disturbed coal, the corresponding gas content can be as high as 21.68 m^3/t because of the sorption properties of the particular coal (Liu, *et al*., 2011). It has been demonstrated in some Australian mines through grunching and remote mining that, in some areas, there can be no outburst when the gas content was as high as 14m^3/t. It however raises the question, as suggested by Eade (2002), of what the inherent safety factor is for a given threshold value. Also, It has been suggested that CO_2 outbursts are more violent than CH_4 outbursts, but it should be noted that some of the largest outbursts in the world did occur in mines rich in CH_4 (Lama and Saghafi, 2002). As CO_2 is usually associated with structures in Australian mines, can the more violent nature of the CO_2 outbursts be partly explained by the characteristics of the structures that they are associated with besides the higher sorption capacity of coal for CO_2? Lama (1996) however did suggest that the threshold limit value can be increased to 10 m^3/t for 100% CO_2 in the absence of structures. In a mechanistic sense, it is the pressure and relative flow velocity of the free gas which contributes to outburst initiation and evolution. It is therefore important to understand how sorption capacity and rate of desorption affect the temporal evolution of gas pressure around the face in the seam. One may ask whether we should use reservoir pressure instead of gas content as the threshold for outburst management, taking into account the physical properties of the coal and geological structures, and their potential variability in the seam. This however suggests that, in the absence of structures, the gas content threshold value for CO_2 could be higher than CH_4 because of their adsorption properties (adsorption isotherms) even though the threshold values may need to be adjusted for the effects of higher sorption capacity and desorption rate of CO_2 compared to CH_4. There are some other questions that still need to be answered such as what would be suitable threshold values when *in situ* stress and reservoir pressure become higher, permeability may become lower, and CO_2 may exist in a supercritical state as mines get deeper.

NUMERICAL OUTBURST MODEL

Through a number of projects supported by ACARP and CSIRO (Wold and Choi, 1999; Choi and Wold 2003a; Wold, *et al*., 2006; and Choi and Wu, 2008), a numerical model for outburst initiation and evolution was developed by linking a geomechanical model (Choi, *et al*., 1991, 1992; Choi and Tan, 1998) with a coalbed methane reservoir simulator (Spencer, *et al.*, 1987; Stevenson, *et al.*, 1994; Stevenson, 1997). The model can be used to delineate the mechanisms, and to answer some of the questions mentioned. Details of the model and the modelling approaches, and examples of the model application can be found in Choi and Wold (2001a, 2001b, 2003b, 2004), Choi and Wu (2005), Wold and Choi (2001), and Wold *et al.* (2008). The numerical model can be useful where guidance from past experience may not be available. As there can always be some degree of uncertainty with respect to geology, and the variability of the coal and the adjacent rock strata, the main value of the model is its ability to answer some of the "what if" type questions.

OUTBURST MECHANISMS

Laboratory model outburst tests

In order to get a better understanding of outburst mechanisms, it may be useful to look at the results of some of the laboratory model outburst tests which were conducted during ACARP project C13012 (Choi and Wu, 2008). The effects of coal strength, reservoir pressure, pressure gradient and gas composition on outbursts are demonstrated by the experimental results.

The model outburst tests were conducted using a cavity index cell as shown in Figures 1 and 2. The cell was initially developed for laboratory cavity completion experiments (Wold, *et al*., 1994; Paterson and Wold, 1995). The sample was placed into the cell by sliding it inside the rubber membrane. The back end of the sample rested against the end cap which had a port through which pore pressure could be measured. Steel rings with a central hole could be inserted between the sample and the end cap to ensure that the sample was thrust against the end cap.

During the model outburst tests, the gas pressure at the front was released by opening the air operated valve (see Figure 2), the pressure could be reduced to atmospheric pressure in the order of 200-300 milliseconds.

The cylindrical piston applied a compressive stress to the front end of the sample during the application of the pore pressure, and held the sample in place against the forces generated by the back pressure during the outburst experiments. The free surface area of the sample during the tests was that within the 30 mm inner diameter of the piston. The gas was discharged into an expansion chamber-muffler and the coal which was ejected during the outburst test was collected in a bag.

The results show that, if the gas pressure in the coal samples is higher than a certain value for a given uniaxial compressive strength, outburst will be induced with the formation of a cavity (see Figures 3a and 3b). The size of the cavity is larger at higher gas pressure and for weaker coal. Discing can occur at higher pressure (see Figure 4). However, for tests under the same gas pressure and for coal samples with similar strength, no apparent difference in the size of the cavity was observed.

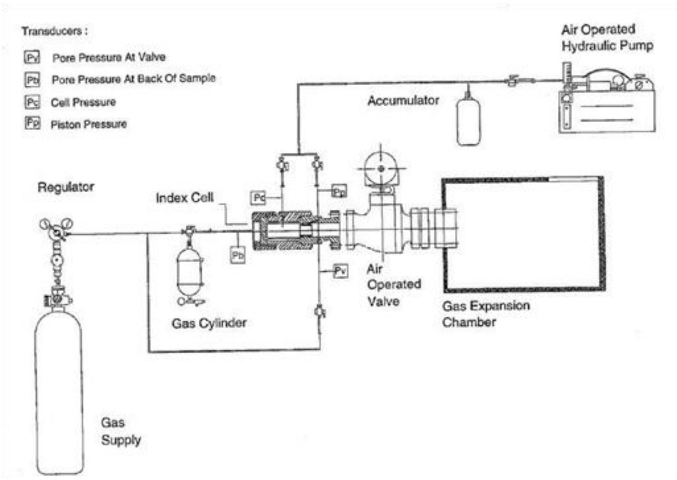

Figure 1 - Experimental set-up of model outburst tests

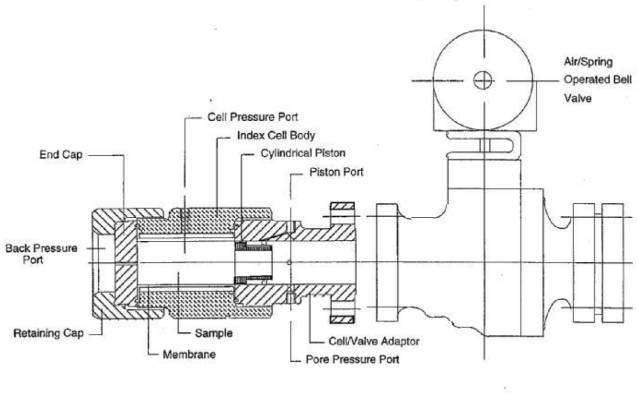

Figure 2 - Closer view of test set-up

Figure 3a - Formation of cavity in laboratory model outburst experiment

Figure 3b - Shape of cavity by pouring plastic into the cavity after the outburst experiment

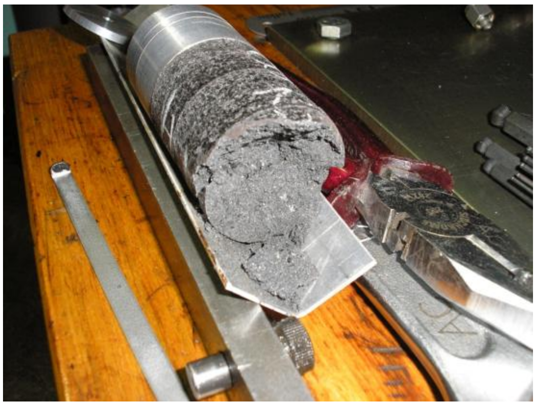

Figure 4 - Appearance of test sample showing both cavity and discing type failures

SOME CONCLUSIONS DERIVED FROM OUTBURST MECHANISMS AND THE NUMERICAL OUTBURST AND GAS DRAINAGE MODELLING STUDIES CONDUCTED TO DATE

It was found that, from the work conducted in some of the earlier ACARP projects (Wold and Choi, 1999; Choi and Wold, 2003), for outburst risk analysis and for outburst control and management, it is important to be able to assess both the likelihood of an outburst event and the consequence in case such an event does happen. As risk is measured in terms of likelihood and consequence, the risk control measures can be dependent on the potential consequence.

A series of parametric studies was conducted using the "coupled" model to identify which are the key variables in outburst initiation, and which are the less important variables. These model results strongly support the importance of gas pressure and pressure gradient, coal strength and geological structures in determining threshold values for outburst risks. Some later work also suggested the importance of porosity and pore structure (including the geometry of the fracture network).

The influence of other variables such as the orientation of the principal components of the *in situ* stress, the effects of changes in stress on permeability, rate of mass transport between adsorbed gas and free gas, and heading advance rate were also studied. A certain degree of understanding of the significance of those variables on outburst initiation was obtained. However, in contrast to the general experience that areas of high CO_2 content are more hazardous with respect to outburst compared to areas with high CH_4 content, the model predicted, under the modelled conditions, a slight reduction in outburst initiation potential with an increase in the CO_2 proportion in the gas composition for the same initial reservoir and desorption pressures. The higher rate of desorption for CO_2 compared to CH_4 may however play a certain role during post-initiation outburst evolution. As CO_2 can cause a higher degree of coal matrix swelling/shrinkage compared to CH_4 when undergoing similar change in desorption pressure, strength reduction associated with CO_2 adsorption/desorption can be explained by the mechanical damage that is caused by the differential swelling/shrinkage as the strain distribution at different distances from the coal surface is not uniform. It should however be noted that no apparent difference in the size of the outburst cavity was observed for the laboratory model outburst tests conducted on coal samples with similar strength under the same gas pressure.

Gas drainage to below the gas content threshold values would be much more difficult for CO_2 than CH_4 because of the much lower desorption pressure for CO_2 corresponding to the threshold gas content value, this would imply a much higher degree of reservoir pressure drawdown (or drainage) is required for CO_2. Application of suction would have obvious benefit for CO_2 drainage. Borehole inclination for long drainage holes may also have an important impact on CO_2 drainage because of the hydrostatic pressure from the water in the borehole.

An outburst occurs whenever the force provided by the gas at a given pressure gradient is enough to mobilise and transport the coal at the face. The required force is a function of the strength of the coal at its current state. Post-initiation evolution depends on additional factors such as fracture toughness (which is very low for sheared or mylonitised coal but can be quite high for some strong coal) and the source of free gas. Outburst occurs whenever the conditions are satisfied, including at shallow depths. Outburst management based on gas composition and gas content threshold values can be either under- or over-conservative even though outbursts that occur below the threshold gas content value are expected to be "mild".

Geological structures play a role in outburst through modifying the strength, permeability and/or porosity and pore structure of the coal, the amount of free gas, and/or pressure and pressure gradient.

Because of the difficulty of detecting some small local heterogeneity such as some pockets of very weak materials, some very small scale "outburst" is difficult to avoid. For some cases, body force due to gravity can contribute to an outburst.

Gas desorption rate may or may not play an important role depending on how it may contribute to the spatial and temporal variation in pressure distribution as mining progresses. For rate of desorption to have an important impact during an outburst the coal has to be in the form of very small particles. Mylonitic coal can be more outburst-prone simply because of its low strength and higher porosity than normal coal.

During an outburst, the first law of thermodynamics (or the law of conservation of energy) is obeyed. By identifying all the different forms of energy that are available in the system to drive an outburst and the energy that is required for the different processes during an outburst, it should be possible to make some initial assessment whether an outburst is likely to occur and the scale of a potential outburst.

Based on the underlying mechanisms, outburst prevention can be through reduction of pressure and pressure gradient (such as gas drainage) and/or minimisation of mechanical damage to the coal (through stress relief or strengthening of the coal), or by reducing the pressure gradient and hydrodynamic forces and energy (such as filling the pore space with a much less compressible fluid) that is available to dislodge and transport the coal.

By considering the outburst mechanisms and the first law of thermodynamics, and taking into consideration the effect of porosity on the pressure gradient and hydrodynamic forces, the current gas content threshold value can be too conservative for some low permeability but reasonably strong coal.

The numerical outburst model is able to predict how pressure, the relevant strength parameters and stress around the face evolve as mining progresses. However, one of the major challenges is the availability of field data, including the detection and characterisation of outburst prone structures.

It is possible that all outbursts are associated with some types of structures (including cleat fractures), whether they are pre-existing or mining induced unless the coal is inherently very weak for some reasons.

It may be more important to ensure that the pressure in the outburst prone structures has been reduced to below a certain critical level than trying to reduce the gas content of the seam.

For seams with very low permeability and porosity, reasonably strong coal, and if there is no problem with mine air ventilation and other gas issues, it may be even safer to mine without gas drainage (to keep the seam fully water saturated) under certain conditions.

It may be more important to use drainage holes to ensure that sufficient gas will be drained from outburst prone structures and to monitor reservoir pressure in addition to gas content. One major issue is the integrity of the drainage holes as mylonite, sheared coal and coal associated with other outburst prone structures can be weak. In grounds with high *in situ* stress, borehole stability can be a problem. Borehole collapse may occur leading to blockage of drainage holes, which can lead to difficulty in draining the gas and allowing pressure to build up. Drainage may not occur where it is needed most.

APPLICATION OF THE NUMERICAL OUTBURST MODEL FOR OUTBURST CONTROL AND MANGEMENT

The main advantage of the numerical outburst model is that outburst prediction can be made based on the conditions of the mine, and it can be used to predict how the various field variables such as pressure and stress, and coal properties may change as mining progresses, and the model can be updated if new information becomes available such as the detection of some previously unknown structures. Another major advantage is that sensitivity analyses can be conducted to predict different possible outcomes by taking into account the uncertainty in some of the field data (Wold, *et al*., 2006; 2008). The model can also be used to predict what would be the likely mechanism for outburst occurrence with the given field data. Advancement in *in situ* measurement and ground characterisation ahead of mining and roadway development would certainly be useful in providing the required data, and in improving the accuracy of the model predictions.

CONCLUSIONS

The current use of gas content threshold values for outburst control and management has been very successful in preventing major outbursts from happening. It is apparent that the inherent safety factor for any adopted value can be different for different mines, and at the different stages of mining and roadway development. As it is largely an empirical approach, there are a number of questions that still need to be answered. The adoption of overly conservative gas content threshold values may cause some operational issues for some mines. Use of gas pressure instead of gas content threshold as one of the indices for outburst prediction is practised in some coal mines in China. The main difficulty in outburst prediction is that outburst is a phenomenon which involves the interaction of a number of factors and processes. Any analytical or numerical approach for outburst prediction needs to be able to account for the individual processes and their interaction, it is here where the numerical outburst model that has been developed to date would be useful. The model can be used to help a particular mine to identify the major mechanisms and critical factors for outburst control and management purpose. Based on the assessed risk and any major operational issues, one may choose complete prevention or suitable control and management measures may be chosen without undermining safety.

ACKNOWLEDGEMENTS

The author would like to acknowledge the financial support he received from ACARP and CSIRO for the work reported in this paper. The important contribution in a number of ACARP projects by his former colleague, Mr Mike Wold, is also gratefully acknowledged. The author would also like to thank Mr Jeff Wood, Mr Russell Howarth and Mr Roger Wischusen for their useful input, comments and suggestions while acting as project monitors on behalf of ACARP. The author would also like to thank his CSIRO colleagues, Dr Bailin Wu, Mr Leo Connelly, Mr Greg Lupton and Mr Michael Camilleri for their contribution towards some of the projects. The support provided by Mr Bruce Robertson through his active interest in outburst research is also gratefully acknowledged. The author would also like to thank, among others, Dr Ray Williams, Mr John Hanes, Mr Brad Elvy and Mr Russell Thomas for their help.

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