2004

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Publication Details

This conference paper was originally published as Choi, X & Wold, M, Study of the Mechanisms of Coal and Gas Outbursts Using a New Numerical Modeling Approach, in Aziz, N (ed), Coal 2004: Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy, 2004, 181-194.

STUDY OF THE MECHANISMS OF COAL AND GAS OUTBURSTS USING A NEW NUMERICAL MODELING APPROACH

Xavier Choi [1] and Mike Wold [2]

Abstract: During mining or roadway development, the distribution of stress and pore pressure in the coal face and rib around the new opening will change. These changes are usually dependent on the mining history and are related to the rate of roadway development, geometry of the opening, the pre-mining stress and reservoir conditions, the strength of the coal, the adjacent rock strata and major geological structures, and the permeability of the coal. Quasi-static yielding of coal is usually observed at regions of high stress concentration. However, under certain conditions, dynamic failure of coal in the form of an outburst can occur.

The occurrence of coal and gas outbursts and the way they evolve will depend on a number of factors and processes. Under varied mining conditions, some of the factors and/or processes may play a more important role in outburst initiation than others. It can be misleading to attribute the cause of an outburst to a particular factor or process. This is partly because some of the processes are highly non-linear; outburst occurrence may depend on how these processes evolve and interact. The problem becomes more complex because natural heterogeneity of the coal and geological structures also play an important part in the outburst mechanisms.

In the modelling studies presented in this paper, an outburst is considered to consist of three distinct stages: pre-initiation, initiation and post-initiation (or outburst evolution). During the pre-initiation stage, deformation of the yielded coal occurs in a quasi-static manner. Initiation is referred to as the moment in time when the deformation behaviour of the coal/rock/gas system suddenly transforms from being quasi-static to dynamic. The post-initiation stage, or outburst evolution, is characterised by the release of a substantial amount of gas and violent ejection of coal fragments into the mine opening. A description of the numerical modelling approach is given in this paper, and model results, including the post-initiation deformation and fragmentation of the ejected coal, are presented. The effects on outbursts of gas content, gas composition, pressure gradient, coal strength and other factors are discussed.

INTRODUCTION

During mining or roadway development, a change in stress and pore pressure around the new opening occurs. At some stage, an outburst may be initiated which can be related to the size of the opening and/or the proximity to some geological structures. When outbursting occurs, the rock/coal/gas system transforms from a stable to an unstable state with the release of a significant volume of gas over the duration of the outburst. Some mechanisms that enable the system to overcome the energy barrier provided by the strength of the coal must exist. They can be related to major geologic structure, natural heterogeneity, and/or the state of the system. Although an outburst may sometimes be referred to as "instantaneous", the system may, in some outbursts, go through several meta-stable states before reaching the final equilibrium state, and the whole process may take many seconds or minutes. As coal is a soft rock, the amount of strain energy stored as a result of elastic deformation is limited. In order for coal to fail in a violent manner, another form of energy needs to be available. This is supplied by the adsorbed gas within the coal matrix and the compressed gas in the void space such as the cleats and other natural fractures. Pre-mining gas drainage is effective in preventing outbursts by removing this source of potential energy.

After an outburst has been initiated, the outburst coal starts to deform at a high strain rate, and the fragmented coal will tend to behave as a particulate material. Depending on the gas pressure and the availability of new sources of free gas, the gas can cause further failure and fragmentation of the coal, and the expanding gas will

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provide a drag force to propel the fragmented coal further into the mine opening. During an outburst, fluid flow in the outburst coal will transform from flow in a fractured porous medium to dense particle flow where the consideration of inter-particle contact and collision is important, and then to dilute particle flow as the ejected coal fragments and particles move further away from each other. At this stage, the momentum transfer between the coal fragments and free gas emitted from the mine face becomes important.

NUMERICAL MODELLING APPROACH

Numerical modelling of outbursts requires the quantification of a number of processes and factors and their interactions shown in Figures 1 and 2. These include gas desorption, mass transfer between adsorbed gas and free gas, flow of water and gas within the cleats, macropores and other large scale fractures, coal deformation and failure, coal fragmentation, gas dynamics and transport of outburst coal (particle flow).

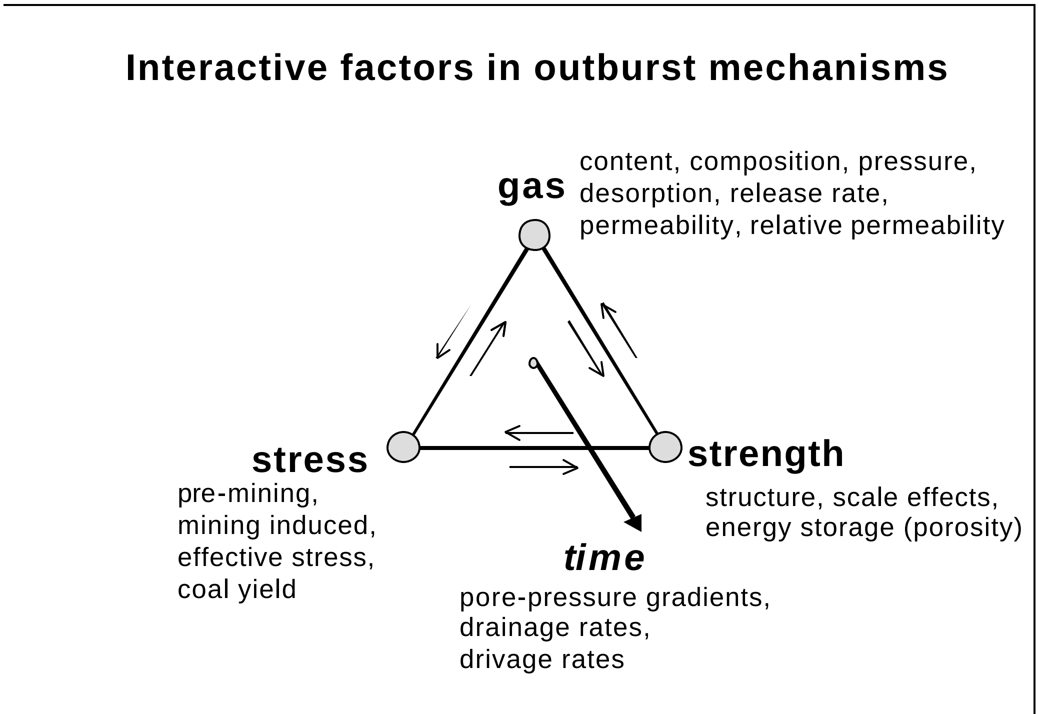

Fig 1 - Schematics of interactions of reservoir, geomechanical and time rate variables contributing to outburst mechanisms

A numerical model for outburst initiation was developed by linking a geomechanical model (Choi, 1984; 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 has been applied to study the mechanisms for outburst initiation (Choi and Wold, 2001a and 2001b) and to identify which are the key variables in outburst initiation, and which are the less important variables (Wold and Choi, 1999). The capability of the numerical model for outburst initiation has been extended to include development of additional constitutive models for the important factors and processes that occur during the post-initiation evolution of outbursts (Choi and Wold, 2002).

In the modelling studies, pre-initiation quasi-static yielding type failure of coal is distinguished from the post-initiation failure of outburst coal, as the latter is much more dynamic and violent, involving fragmentation of the coal and rapid release of gas. The quasi-static yielding failure is modelled using macroscopic plasticity theory with softening, and the fragmentation process is modelled using continuum damage mechanics. The effects of particle size on the rate of mass transfer between adsorbed gas and free gas during fragmentation are studied using both the more conventional two-stage desorption diffusion processes and a new hypothesis based on the kinetics of desorption. The violence of the model outburst is estimated using the momentum of the outburst coal. The potential volume of gas that can be released immediately after an outburst is estimated based on the amount of desorbable gas in the ejected coal and the gas flux from the faces.

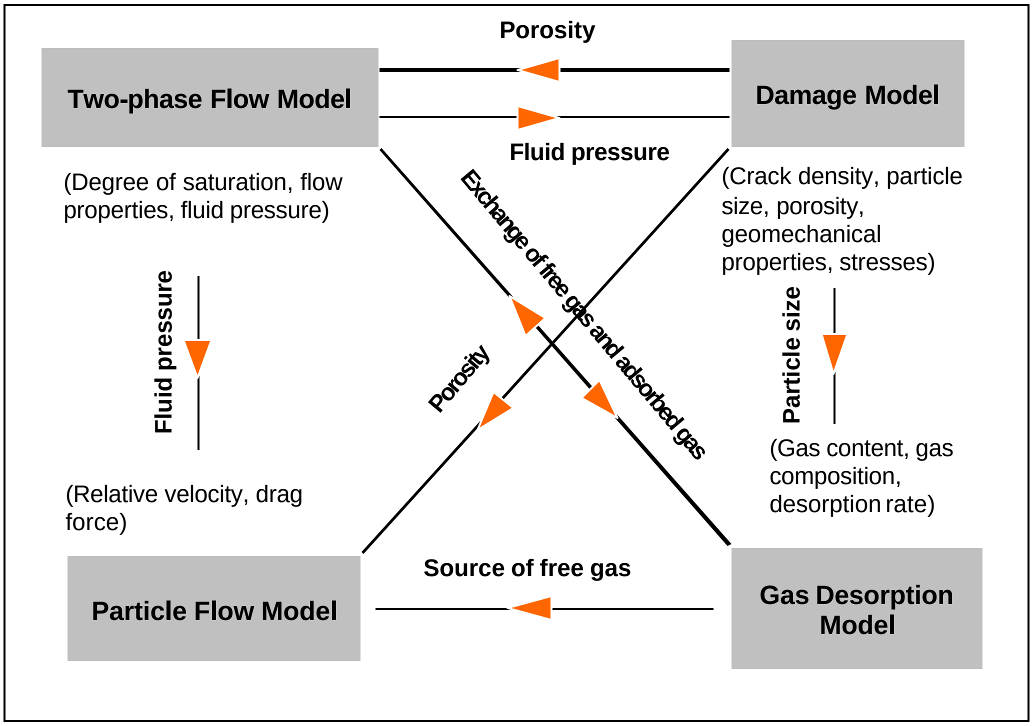

Fig 2 - Schematics of coupling of major processes in modelling outburst evolution

GAS ADSORPTION AND DESORPTION

As most of the gas in coal exists in the adsorbed state on the surface of micropores within the coal matrix, it is important to understand the gas adsorption/desorption properties of coal and the mechanisms of mass transport between adsorbed gas and free gas, and how the adsorbed gas may become available as free gas to provide the energy during an outburst.

The adsorption properties of coal are normally represented by the adsorption isotherm which shows the amount of gas adsorbed at a certain temperature and partial pressure. For a single component gas, the Langmuir adsorption isotherm (Langmuir, 1918) is usually used for coal and is given by

$$\frac{V}{V_L} = \frac{p_g}{P_L + p_g} \qquad (1)$$

where V is the volume of gas adsorbed per unit mass of coal at pressure p_g, V_L is the Langmuir volume, which is the volume of gas needed for monolayer coverage of the surfaces of the micropores per unit mass of coal, and P_L is Langmuir pressure, defined as the pressure at which the volume of gas adsorbed is half the Langmuir volume.

The extended Langmuir model (ELM) is the most common approach used to represent multicomponent gas adsorption in coal. This is based on direct extension of the single component isotherm to a multicomponent system giving the analogous expression

$$\frac{V_i}{V_{Li}} = \frac{b_i p_{gi}}{1 + \sum_{j=1,n} b_j p_{gj}} \qquad (2)$$

where subscript i represents the i^{th} gas component, b is the reciprocal of P_L, and n is the number of gas components.

After initiation, the way an outburst evolves can be strongly influenced by the amount of free gas in the outburst coal. It is therefore important also to understand the kinetics of the adsorption and desorption processes, and the rate of transformation of adsorbed gas into free gas during an outburst.

In the Langmuir treatment of the kinetics of gas adsorption and desorption, equilibrium condition is obtained by equating the rate of adsorption to the rate of desorption as follows:

$$\frac{P}{\sqrt{2\pi m k T}}(1-\theta) = \frac{e^{-Q/kT}}{\tau_o a}\Theta \qquad (3)$$

where P is gas pressure, m is the mass of the gas molecule, k is Boltzmann constant, T is absolute temperature, θ is fraction of available sites occupied $(0 \le \theta \le 1)$, Θ is total surface area of adsorption sites, Q is energy of adsorption, a is the area of an adsorption site, and τ_o is the average resident time.

It was observed by Groszek (1982) that, at very low pressure, very little energy is required for the adsorbed molecules to move away from the interface, and the rate of desorption can be very high.

In the conventional approach, the rate of mass transport between adsorbed gas in the matrix and free gas in the cleats and other fractures is assumed to involve a two-step process corresponding to desorption/diffusion within the coal matrix, followed by long-range flow in the cleat system. Desorption of gas from the coal surface occurs at a much faster rate than the diffusion of the gas through the coal matrix. The rate of diffusion is often assumed to be sufficiently represented by Fickian diffusion which is usually the rate-limiting step in the desorption process.

If the coal matrix can be assumed to be made up of spheres with a characteristic radius (Ancell et al., 1979, 1980), the rate of mass transport between free gas in the cleats and adsorbed gas within the coal matrix is given by

$$\frac{c_d}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial c}{\partial r}\right) = \frac{\partial c}{\partial t} \qquad (4)$$

where c_d is the micropore diffusion coefficient, c is gas concentration, and r is radial distance from the centre of the sphere. The rate of mass transfer therefore depends on the characteristic radius of the spheres, the micropore diffusivity, the partial pressure of the free gas in the cleats, and the gas content (or concentration of gas in the matrix spheres).

However, considering that small fragments and fine particles can be generated very rapidly during an outburst with loss of confinement and rapid drop in pressure around the particles, rapid gas desorption will occur. At the time when the particles have just been formed, it is assumed that the gas content and pressure within the particle is uniform. An amount of free gas resulting from the formation of the new surfaces will be available, together with the gas in the bulk phase existing in the pores that are connected to the new surfaces. The adsorbed gas in the very small particles may transform into free gas in a very short time. For the larger particles, a high pressure gradient will exist within the particles, and viscous flow, in addition to Fickian diffusion, will become an important mass transport mechanism within the matrix. Within the particles, it is assumed that the viscous flow can be adequately represented by Darcy's law :

$$u_i = -\frac{k}{\mu}\frac{\partial p}{\partial x_i} \qquad (5)$$

where u_i is apparent velocity, k is permeability, μ is viscosity, x_i is spatial coordinate.

In 3-dimensional Cartesian space, taking into account desorbed gas as a source for free gas, and assuming that the change in porosity and gas density over a small time step can be ignored, the continuity equation is given by

$$\frac{\partial V}{\partial t} = \frac{1}{\rho_s}\nabla \bullet u_i = \left(\frac{V_L}{P_L + p_g}\right)\left(\frac{p_g}{P_L + p_g}\right)\frac{\partial p_g}{\partial t} \qquad (6)$$

where ρ_s is the density of coal.

Equation (6) can be used as the source term in the mass balance and momentum equations to calculate gas flux and drag force acting on the coal fragments.

COAL DEFORMATION AND FAILURE – CONTINUUM STATE

During mining of a roadway, stress concentration will occur in certain regions around the mine opening. Under sufficiently high stress, initiation and growth of microcracks can occur. Initially, this will tend to occur in a smooth and gradual manner, and the differences between the states at each stage of progressive failure can be very small, with a smooth transition from intact to failed state. Failure at this stage may manifest itself as plastic deformation resulting from distributed damage evolution, strain localisation, subcritical crack growth and coalescence, and degradation of mechanical properties including strength and bulk and shear moduli. The degree of "plastic" damage just prior to outburst occurrence can have important influence on the fragmentation process during post-initiation outburst evolution. However, the plastic damage is rate-independent while the post-initiation damage (or fragmentation) is strongly rate-dependent. It is therefore important for the two distinct stages of failure to be modelled using different approaches.

The Mohr-Coulomb criterion is used to represent the shear failure of coal. In the modelling studies, after yielding has occurred, the total strain is assumed to consist of three components: the elastic, plastic and damage components.

$$\varepsilon = \varepsilon^e + \varepsilon^p + \varepsilon^d \qquad (7)$$

Damage (or material degradation) is expressed as a function of total plastic strain.

$$D = 1 - e^{-\alpha\varepsilon_p} \quad (0 \le D \le 1) \qquad (8)$$

The elastic properties of the coal continues to change as the degree of damage increases.

$$c_d = c_o(1 - \chi D) \qquad (9)$$

$$\phi_d = \phi_o(1 - \beta D) \qquad (10)$$

$$E_d = E_o(1 - \gamma D) \qquad (11)$$

$$\upsilon_d = \upsilon_o(1 - \kappa D) \qquad (12)$$

where c is cohesion, ϕ is angle of internal friction, subscript o represents the initial (undamaged) material property, subscript d represents the damaged material property, and the values for α, χ, β, γ, and κ have to be determined in the laboratory under triaxial compression to beyond the peak strength, under strain-controlled conditions.

COAL FRAGMENTATION

When an outburst has been initiated, macroscopic continuum damage mechanics is adopted to model the creation of new cracks, and the propagation and coalescence of new and existing cracks. Although it is less rigorous than the micro- and meso-damage approaches, it provides a computationally feasible alternative for some complex problems such as the modelling of rock fragmentation. The constitutive models are based mainly on experimental observations at the macroscopic scale (Grady and Hollenbach, 1979; Kipp et al., 1980). It is assumed that the fragmenting coal can be treated as an isotropic, continuous and homogeneous material with pre-existing microcracks. The outburst coal is considered to deform at a high strain rate, and confinement will be lost after the coal has detached from the face. The coal will continue to deform under the influence of the free gas in the pore space, and is subjected mainly to tensile stress induced by the compressed gas. The propagation of the pre-existing microcracks occurs mainly under mode I (opening mode), and damage is isotropic. Based on the above assumptions, damage can be sufficiently represented by a scalar variable. It is also assumed that a critical strain criterion can be used to predict the onset of fragmentation. The assumption of isotropy enables the use of a model which is tractable and requires only a few model parameters that are physically meaningful. Most importantly, their values can be measured in the laboratory.

In the model, the degree of damage to the outburst coal is a function of strain rate. The coal is assumed to be completely destroyed (or lose its strength and stiffness) when the crack density has exceeded a certain critical value for a particular type of coal. This is reflected by the values of effective bulk modulus and Poisson's ratio both approaching zero. The size of the fragments is assumed to be directly related to the maximum strain rate experienced during the loading history. Based on the above assumptions, the model can therefore be represented by the following equations to provide an initial estimate of particle size. Subsequent size evolution may depend on other factors such as collision among particles, but they are not considered here.

$$F = 1 - e^{-\alpha C_d} \tag{13}$$

$$\upsilon_e = \upsilon(1 - \beta F) \tag{14}$$

where $$\lim_{C_d \to \infty} \beta = 1 \tag{15}$$

$$K_e = (1 - \gamma F) K \tag{16}$$

$$r = \omega \left(\frac{K_{IC}}{E_{eff} R} \right)^{2/3} \tag{17}$$

$$c_d = f(\varepsilon_{dp}) \left(\frac{K_{IC}}{E_{eff} R_{max}} \right)^2 \tag{18}$$

C_d is crack density, F is regularised damage parameter, u is Poisson's ratio, K is bulk modulus, K_{IC} is mode I fracture toughness, r is radius of fragment, R is strain rate, R_{max} is maximum strain rate during loading history, ε_{dp} is cumulative irreversible strain due to plastic deformation and damage, and subscript e refers to effective material property. α, β, γ, ω, and E_{eff} are empirical constants and material properties that need to be determined through laboratory measurements.

Gas dynamics and transport of outburst coal

Particle flow refers to the two-phase (particles and fluid) flow where solid particles are immersed in a continuous carrier fluid (liquid or gas). These correspond to the fragmented coal and free gas during an outburst in which the fragmented coal is expelled into the mine opening by the gas. In modelling particle flow, two conditions have to be distinguished – dilute flow (the solid particles are highly dispersed) or dense flow. For dilute flow, the solid and fluid mixture may be treated as single-phase fluid with modified rheological properties. However, for dense flow, which is more related to the early stages of coal ejection from the face, the mixture has to be treated as a two-phase medium, taking into consideration the interaction between the coal fragments and the continuous fluid phase.

As the number and size of the particles (or coal fragments) are not constant, but constantly evolving, and due to the very large number of fragments, it is almost impossible to model them explicitly. Instead, the coal fragments and the carrier fluid are treated as two super-imposing continua. For such a case, the particle flow can be represented by the Navier-Stokes equations for compressible gas, and the interaction between the coal fragments and the carrier fluid can be represented by suitable interfacial exchange terms in the momentum equations

$$-2\mu_s \nabla \bullet \left(\phi_s \varepsilon(u_s)\right) + \rho_s \phi_s (u_s \nabla) u_s = -\phi_s \nabla p_f + M + \phi_s F_b \tag{19}$$

$$-2\mu_f \nabla \bullet \left(\phi_f \varepsilon(u_f)\right) + \rho_f \phi_f (u_f \nabla) u_f = -\phi_f \nabla p_f + M + \phi_f F_b \tag{20}$$

The drag force (Ergun, 1952) of the gas on the coal fragments (assumed to be spherical) is given by

$$F_d = f(n, Re) \frac{\pi}{4} d_p^2 \frac{\rho_g u_r^2}{2} \tag{21}$$

where

$$Re = \frac{u_r d_p \rho_g}{\mu_f} \tag{22}$$

f is volume fraction, *u* is velocity, *m* is viscosity, *r* is density, *e* is stretch tensor, *p* is pressure, *M* is interfacial momentum transfer, F_b is body force, *n* is local porosity, *Re* is Reynold's number, d_p is average particle diameter, u_r is relative velocity, subscript *f* is fluid phase, and subscript *s* is solid phase.

To model the violence of outbursts, it is necessary to calculate the initial momentum and the initial drag force of the expanding free gas on the motion of the coal fragments. After expulsion from the face, the coal fragments are travelling at reasonably high speed and desorbing gas at the same time. Further fluid-particle interaction is not tracked. It is considered that the initial momentum gives a good indication of the violence of the event.

MODEL DESCRIPTION

All the model studies were conducted using a 2-dimensional geometry. The seam is at a depth of 500 m. The roadway is 5 m wide. The coal was assumed to be homogeneous. Heading advance of 25.0 m was modelled in five stages, each of 5.0 m, and each of uniform time increment to simulate a rate of 14.0 m/shift. Geological structures such as faults and dykes were included in some of the studies (see Figure 3). The input values for some of the model parameters are shown in Tables 1 and 2.

Table 1 - Values of parameters used in strain softening model

α	χ	β	γ	κ
100.0	1.0	0.0	0.0	0.0

Table 2 - Values of parameters used in fragmentation model

Critical strain (fragmentation)	α	β	γ	f (ε_{dp})
0.3	1.0	0.0	1.0	ε_{dp}

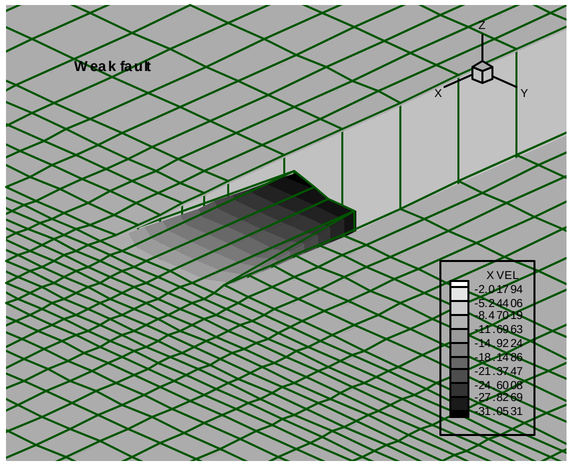

Fig 3 - Velocity (m/s) contours during model outburst when mining through weak fault.

MODEL RESULTS

The Effects of Coal Strength

It appears that, if the strength of the coal is high enough, outburst will not occur (see Figure 4). Also, the degree of violence seems to decrease with an increase in coal strength (see Figures 4 and 5). Furthermore, model failure of the very strong coal occurred mainly in a small region behind the face, and stress arching in the intact coal further back behind the face provided a stabilising mechanism against outburst initiation.

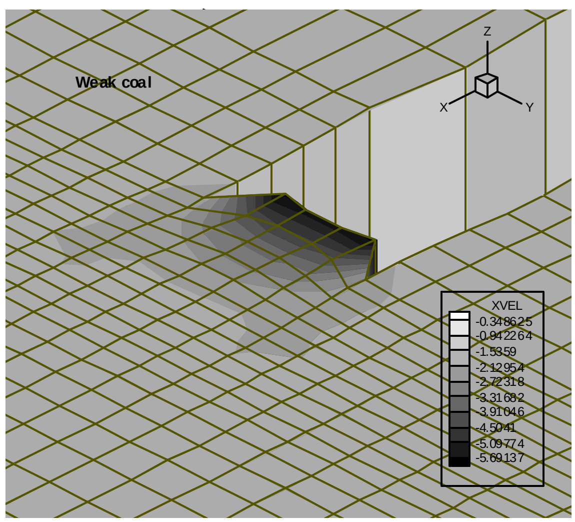

Fig 4 - Velocity (m/s) contours during model outburst in weak coal

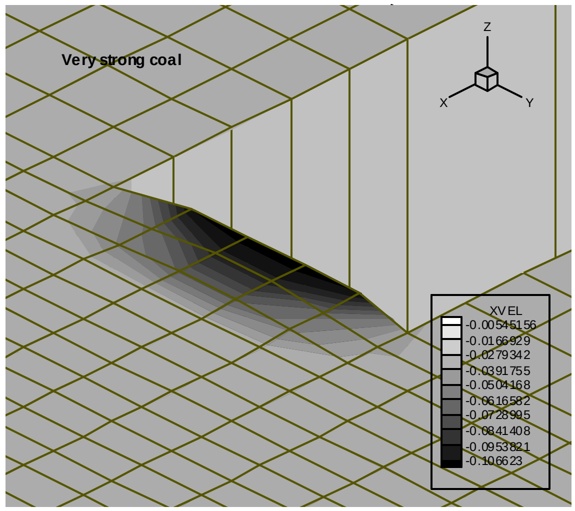

Fig 5 - Velocity (m/s) contours during model outburst in very strong coal

The Effects of Fragment Size and Gas Desorption Rate using the Conventional Approach

The effects of fragment size on the rate of desorption and the mass transport of desorbed gas to the cleats were first modelled by varying the desorption time constant using the conventional approach (see Equation 4). It can be seen from Figures 6 and 7 that the difference in pressure gradient at the face between seams saturated with either CO_2 or CH_4 is less than 10%.

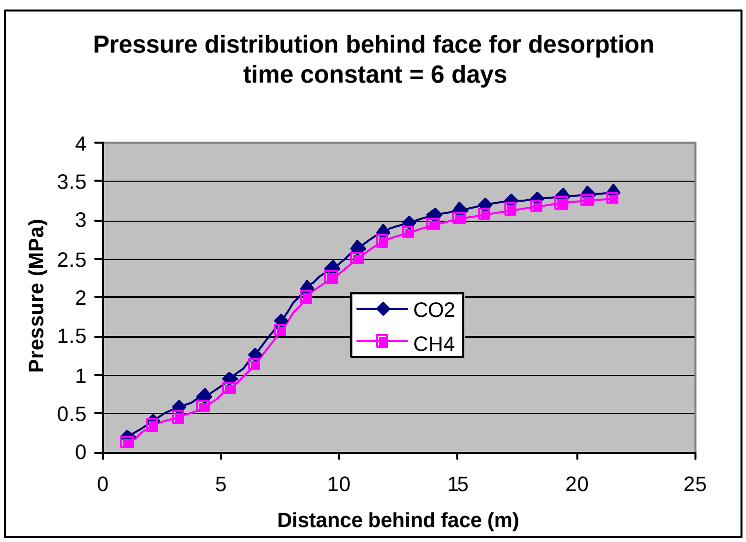

Fig 6 - Pressure distribution behind face for desorption time constant = 6 days

This does not provide a good explanation for the observed difference in violence between CO_2 and CH_4 outbursts. Also, there was significant decrease in the pressure and pressure gradient behind the face as the desorption time constant was reduced from 6 days to 8.5 seconds. This would imply that, based on geomechanical considerations, an outburst is less likely to be initiated with a decrease in desorption time

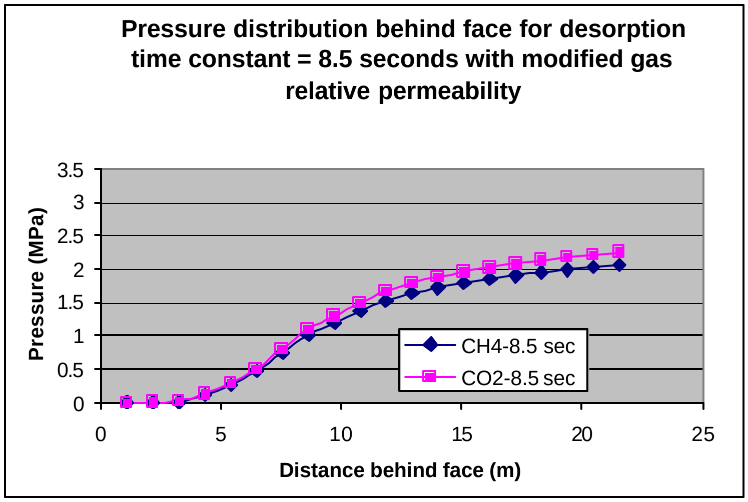

Fig 7 - Pressure distribution behind face for desorption time constant = 8.5 sec with modified gas relative permeability

strain rate, and the voids in the coal will expand rapidly, leading to almost full saturation of void space by gas and significant increase in permeability and the relative permeability factor. It was found in the modelling studies that this could lead to a very significant increase in drag force with a great influence on the post-initiation behaviour of the outburst coal. The results suggest that the likely impact of an increase in desorption rate is on post-initiation behaviour during outburst evolution.

The Effects Of Gas Diffusion Mechanism And Gas Composition Using The New Approach

If we assume that desorption is almost instantaneous and that viscous flow within the coal fragments becomes a very important mass transport mechanism under a high pressure gradient, the gas flux at the face for 100% CO_2 can be up to 3 times that of 100% CH_4 in a coal seam with the same initial reservoir pressure. From the model results, based on the gas flux computed at the face for the weak coal, relative velocities between the fragments and the gas were estimated to be about 5 ms^{-1} and 15 ms^{-1} respectively for the cases of CH_4 and CO_2, ignoring the greater amount of CO_2 that might be available due to the creation of the new surfaces. The effects of the higher drag force on outburst violence (increased momentum resulting from greater acceleration) is shown in Table 3. This may explain why CO_2 outbursts are in general more violent than CH_4 outbursts. However, the model results still need to be validated against data from laboratory tests or field observations. The model results suggest that CO_2 may not increase the likelihood of an outburst, but that its influence is mainly to increase the violence of an outburst after it has been initiated. It should be noted that, based on the model results, the controlling factors for outburst initiation are pressure and pressure gradient, and the former is directly related to gas content through the desorption isotherm. This would imply that, depending on the gas adsorption properties of the coal, the reservoir conditions for outburst initiation may correspond to different gas contents. Unless there is significant influence of CO_2 on coal strength, or the amount of dissolved CO_2 in the pore fluid can provide a significant amount of free gas during an outburst, the model results would imply that, if other geological factors are similar, CO_2 outbursts would occur at a higher gas content compared to CH_4 outbursts, and that CO_2 outbursts, once initiated, are likely to be more violent.

Table 3 - Acceleration caused by drag force

Radius of Particle (mm)	Relative Velocity (ms^{-1})	Drag Force (N) * 10^3	Acceleration (ms^{-2})
5	15	7.22	9.84
5	10	4.81	6.56
5	5	2.40	3.28

The effects of geological structures

For structures such as weak faults with high permeability, because of enhanced connectivity to adjacent coal (see Figure 8), pressure in the structure can stay high when the face of the advancing roadway is very close because of the inflow of gas from the coal to the structure. This can lead to piping and the formation of cavity aligned along the structure as was observed in some of the samples during the laboratory cavity completion tests (Wu at al., 1996). Outburst of this kind of structure can be violent because of the large amount of gas that is available to drive the outburst.

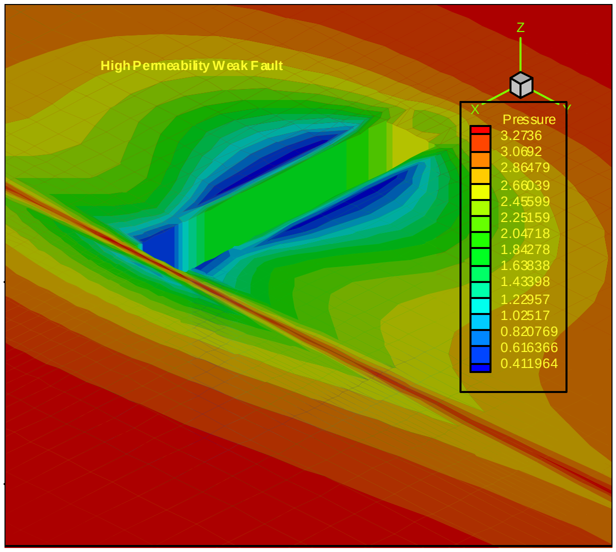

Fig 8 - Pressure distribution in weak fault behind face

Volume of outburst coal and gas

Damage reduces the strength and stiffness of the coal. By using the values for the parameters in the damage models and the computed fragment size as shown in Table 4, the volume of outburst coal appears to be smaller for stronger coal (see Figures 9 and 10). The volume of released gas associated with an outburst can be estimated based on the amount of desorbable gas in the ejected coal and the gas flux at the faces. However, before applying the model for quantitative prediction in the field, the model parameters have to calibrated for different types of coal, taking into account size effect and heterogeneity.

Table 4. Values of parameters used in fragmentation model and predicted range of particle sizes

ω ($s^{-2/3}$)	(K_{IC}/E_{eff}) $(\sqrt{m})$	Coal type	Smallest particles (m)	Largest fragments (m)
1.0	0.1	Weak	0.093	1.0
1.0	0.1	Uniform	0.115	1.91
1.0	0.1	Strong	0.171	2.18
1.0	0.01	Weak	0.02	0.22
1.0	0.01	Uniform	0.025	0.41
1.0	0.01	Strong	0.037	0.47
1.0	0.001	Weak	0.0043	0.046
1.0	0.001	Uniform	0.005	0.088
1.0	0.001	Strong	0.008	0.101

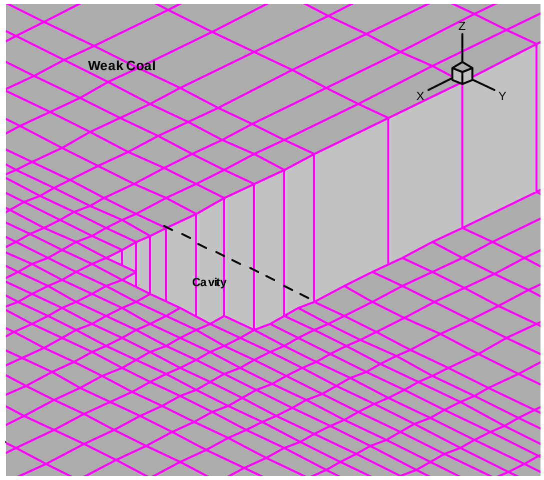

Fig 9 - Model prediction of cavity size in weak coal under model conditions

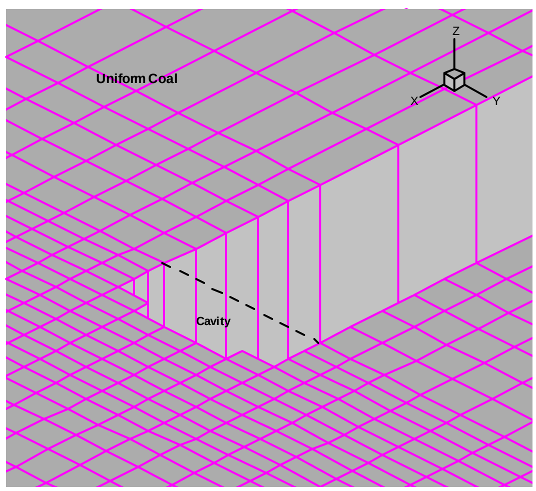

Fig 10 - Model prediction of cavity size in uniform (medium strength) coal under model conditions

DISCUSSION OF RESULTS

The current practice for outburst control and prevention is by gas pre-drainage to below a threshold value of gas content (THV). This can have significant impact on the rate of mine development and production. It is well recognised that permeability is a key factor governing the efficiency and time scale of gas drainage. On the time scale of heading development, i.e. hours or days, low permeability has an important impact on the depth of face drainage and the development of gas pressure gradients, and therefore on conditions for outburst initiation. However, once the outburst event has initiated, virgin permeability is of relatively less significance to the mechanism and the violence of the event.

The model results suggest that strong coals are less prone to outbursts than weaker coals. However, the friability and the rate of damage accumulation under increasing load can affect the rate of strain energy release and stress redistribution. This can have an impact on both the likelihood and the degree of violence of outbursts. Changing the desorption time-constant has little impact on outburst proneness, however, it affects the post-outburst behaviour by providing energy from the expanding gas to drive an outburst and transport the outburst coal through greater drag force. Outbursts associated with geological structures appear to be more violent compared to outbursts in uniform coal.

With respect to gas composition, the model results do not show that outburst will occur at lower gas content for CO_2 compared to CH_4, and in that respect, are compatible with the data collected by Lama (1996), regardless of the superposed THV's. However, at the same initial reservoir pressure, the more violent nature of CO_2 outbursts compared to CH_4 outbursts may be due to the higher rate of mass transport of desorbed gas from the matrix pores to the cracks and other fractures as the coal fragments. In the model, the volume of released gas associated with an outburst can be estimated based on the amount of desorbable gas in the ejected coal and the gas flux at the faces. A mechanism that has been ignored in the current model is the change in sorption capacity of intact coals when they have failed either in shear or tension. It is reported in the literature that the sorption capacity of sheared coal can be much higher than that of intact coal. Although yet to be confirmed through laboratory studies, this could be one of the reasons why the amount of gas released during an outburst is apparently higher than the amount of gas available based on the gas content of the ejected coal. Also, in the modelling conducted to date, the amount of dissolved CO_2 in the pore water has been ignored; it is perhaps worthwhile to estimate the amount of CO_2 that could have been released from solution when the pressure dropped from the initial reservoir pressure to atmospheric during an outburst. The possible influence of CO_2 on the strength and deformation behaviour of coal has also been ignored. If CO_2 does reduce the strength of coal as reported in the literature, it can increase both the proneness to outburst and the degree of violence. This remains to be confirmed by laboratory tests.

CONCLUSIONS

A model has been developed which takes into account the major processes and mechanisms that can influence both outburst-proneness and post-initiation outburst behaviour. The model has been applied to simulate the effects of gas diffusion mechanisms in the coal matrix, coal strength, coal damage, geological structures and gas composition on outbursts. The model is able to provide estimates of the amount of outburst coal and released gas if laboratory data is available for the model input parameters.

The model results do not indicate that coal seams rich in CO_2 are more outburst prone than seams rich in CH_4. On the contrary, because of the higher adsorption capacity of coal to CO_2 relative to CH_4 at the same partial pressure, the results suggest that outbursts tend to be initiated at higher gas content for CO_2 compared to CH_4. On closer examination, the observational data collected by Lama (1996) do not appear to show unequivocally that outburst will occur at a lower gas content for CO_2 compared to CH_4.

The model results suggest that CO_2 outbursts tend to be more violent mainly because of the greater adsorption capacity for CO_2 under the same partial pressure compared to CH_4. After an outburst has been initiated, there is a higher rate of mass transfer of CO_2 from the adsorbed state to the free state, the greater amount of free CO_2 provides more energy to fragment the coal and a greater drag force to act on the fragmented coal, leading to a more violent outburst compared to CH_4 (The possibility of CO_2 causing a reduction in the strength of coal as another contributing factor needs further study).

The likelihood of outbursts appears to be less in stronger coal. Also the degree of violence decreases with an increase in coal strength. It appears that, if the strength of the coal is high enough, the outburst process can be subdued.

For the assumed properties of the structures in the models, the outbursts associated with geological structures such as dykes and faults tend to be more violent compared with uniform coal.

Damage reduces the strength and the stiffness of the coal. The results show that, during an outburst, a substantial amount of energy can be released suddenly, together with transfer of load to the adjacent more intact material. This can cause the adjacent coal to fail and burst. This would suggest that the likelihood of outbursts may increase when the coal is more friable. (The influence of permeability of more friable coal needs further investigation).

ACKNOWLEDGEMENTS

The authors would like to thank ACARP and CSIRO for their financial support for this work. In particular, they are grateful to Mr Jeff Wood who acted as Project Monitor for the ACARP Project, and to Dr Ray Williams of GeoGas for his encouragement and support of the proposal for ACARP Project C9023, and to Dr Eiping Chen of Sandia National Laboratory for his useful discussions on rock fragmentation. They also thank the Australian coal mining community for their continuing support.

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