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TECHNICAL NOTE

Numerical Analyses of the Major Parameters Affecting the Initiation of Outbursts of Coal and Gas

Sheng Xue · Liang Yuan · Yucang Wang · Jun Xie

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List of Symbols

b_i	Body force per unit mass (N/m^3)
C	Average matrix gas concentration (m^3/m^3)
g	Gravitational acceleration (m/s^2)
I	Unit tensor (dimensionless)
$\Delta J_1'$	The first stress invariant (N/m^2)
K	Absolute permeability (md)
k_{rn}	Relative permeability (dimensionless)
P	Pore pressure (Pa)
PL	Langmuir pressure (Pa)
q_{g}	The well flowrate for gas (m^3/day)
q_{w}	The well flowrate for water (m^3/day)
q_{m}	Diffusion and desorption of gas between the matrix and the cleat (m^3/day)
R_{sw}	Gas solubility in water (m^3/m^3)
s	Gas or water shrinkage factor (m^3/m^3)
S	Degree of saturation (dimensionless)
v	Velocity (m/s)
V	Volume of gas adsorbed at pressure P_g (m^3)
V_{L}	Langmuir volume (m^3/m^3)
V_{m}	Bulk volume of a matrix element (m^3)
σ_{ij}	Stress tensor (N/m^2)
ε	Strain tensor (dimensionless)
α	Biot's effective stress parameter
μ_{n}	Viscosity (Pa s)
Φ	Effective fracture porosity (dimensionless)
τ	Sorption time (day)
ρ	Mass per unit volume of the medium (kg/m^3)

1 Introduction

An outburst of coal and gas is defined as the rapid release of a large quantity of gas in conjunction with the ejection of coal, and possibly associated rock, into the working face or mine workings. The sudden and violent nature of an outburst is hazardous through the mechanical effects of particle ejection and by asphyxiation, poisoning, and possible explosion from the gas emitted. With an increase in mining depth and production, the intensity and frequency of outburst tend to increase.

A key challenge to predict and control outburst is to fully understand the major parameters contributing to the initiation of outburst. Previous studies have recognized that these major parameters include stress condition, gassiness of coal seams, geological structures, and mechanical and physical properties of coal (Beamish and Crosdale 1998). It is also widely observed that a coal seam is prone to outburst under the following conditions: high stress, increased mining depth, high gas content, high gas pressure, high gas desorption rate, existence of complex geological structures such as folds, fracturing, faults, dykes, shear zones, magmatic intrusions, and mylonite zones, steeply inclined and

S. Xue (✉) · Y. Wang · J. Xie
CSIRO Earth Science and Resource Engineering, P.O. Box 883,
Kenmore, QLD 4069, Australia
e-mail: sheng.xue@csiro.au

S. Xue
Anhui University of Science and Technology,
Huainan 232001, China

L. Yuan
National Engineering Research Centre of Coal Mine Gas
Control, Huainan 232001, China

thick seam, coal of low strength, and less permeable seam (Lama and Bodziony 1998). These parameters can also affect each other; for example, coal permeability is affected by the stress level and the presence of joints, cleats, and fractures; the stress regime is influenced by geological structures and mining depth; the rate of release of gas from the coal particles is governed by gas content, size of coal particles, or degree of coal fragmentation; and coal strength may be affected by gas pressure and moisture content in coal. The effect of these parameters on the occurrence of outburst is quite complex.

Current knowledge about outburst is largely gathered from field observations and laboratory studies. Recent advances in computer modeling enable the use of numerical simulations to study outburst events, including the contributions and interactions of various parameters on the physical mechanism of outburst. A numerical model permits certain parameters to be varied such that the effects of an outburst can be quantitatively studied.

In this paper, a newly developed outburst simulator is used to analyze major recognized parameters affecting the initiation of outburst. The simulator is developed by linking a geomechanical stress analysis code with a reservoir simulator. The major parameters considered in this numerical analysis include the gas content in coal, coal strength, mining depth, coal permeability, and characteristics of gas adsorption in coal.

2 Numerical Simulator

Previous studies have shown that two conditions must be met in order for an outburst to occur: (1) the coal must be failed under effective stress and the gas must be able to desorb rapidly from the coal, and (2) the gas pressure in the coal must be large enough to push the failed coal into a mining opening instantaneously. In other words, the occurrence of an outburst is the combined result of mining-induced stress redistribution, gas in coal, and the mechanical and physical properties of coal.

Attempts have been made to numerically model the process of the occurrence of outburst. These include a phase transformation model by Litwiniszyn (1985), a gas desorption and flow model by Paterson (1986), a boundary element model by Barron and Kullmann (1990), an airway gas flow model by Otuonye and Sheng (1994), and a fracture mechanics model by Odintsev (1997). More recently, a plasticity model was developed by Choi and Wold (2003) and Wold et al. (2008). The plasticity model attempts to simulate the whole outburst process and, by doing so, a number of assumptions, such as a rate-dependent fragmentation mechanism of coal, are introduced, making the model less robust and many parameters, such as material properties, becoming difficult to calibrate. The plasticity model is also a single-phase (gas) model and does not consider the water which is always present in coal seams and is one of the important factors affecting the initiation of outburst, and its interactions with gas and coal. To address these issues, the authors of this paper developed a coupled numerical simulator to model the initiation process of an outburst through coupling two well-established codes. The simulator is briefly described below and more detailed descriptions about the simulator can be found in Xue et al. (2011).

In the simulator, the deformation and failure of coal are modeled with FLAC3D by the geotechnical analysis of coal and rock, the gas desorption and flow are modeled with COMET3 by analyzing coal–gas characteristics and fluid (water and gas) flow equations, and these two codes are coupled to model the outburst initiation. The basic principle of the coupled model is briefly introduced below.

The continuum form of the momentum principle yields the equation of motion (Eq. 1):

$$\sigma_{ij,j} + \rho b_i = \rho \frac{\mathrm{d}v_i}{\mathrm{d}t} \tag{1}$$

where ρ is the mass per unit volume of the medium, b_i the body force per unit mass, and $\mathrm{d}v_i/\mathrm{d}t$ is the material derivative of the velocity.

Equation (1) is solved with a stress–strain law. The incremental stress and strain during a time step is governed by various elastic or elasto-plastic constitutive laws, which can be written in a general form (Eq. 2):

$$\Delta\sigma' = H(\sigma', \dot{\varepsilon}\Delta t) \tag{2}$$

where H is a given material function, σ' is the effective stress, $\dot{\varepsilon}$ the infinitesimal strain-rate tensor, and Δt is a time increment. The effective stress in Eq. (2) is related to the total stress in Eq. (1) by Eq. (3):

$$\sigma' = \sigma + I\alpha P \tag{3}$$

where α is Biot's effective stress parameter, I is a unit tensor, and P is the pore pressure.

For gas and water flow modeling from coal seams, a dual-porosity model is used, which is based on the idealization of fractured media by Warren and Root (1963). A two-phase flow of gas and water occurs in the fracture or cleat system. The fracture system is assumed to be continuous and provides flow paths to producing wells. Gas is assumed to diffuse from discontinuous matrix blocks into the fracture system. The flow and diffusion systems are coupled by the use of a desorption isotherm at the matrix–cleat interface. For such a dual-porosity and single-permeability system, basic equations governing fluid flow in the coal cleats (fractures) are mass conservations for gas and water (Eqs. 4 and 5):

$$\nabla \cdot \left[b_g M_g\left(\nabla p_g + \gamma_g \nabla Z\right) + R_{sw} b_w M_w\left(\nabla p_w + \gamma_w \nabla Z\right)\right] + q_m + q_g = (d/dt)\left(\phi b_g S_g + R_{sw}\phi b_w M_w\right) \quad (4)$$

$$\nabla \cdot \left[b_w M_w\left(\nabla p_w + \gamma_w \nabla Z\right)\right] + q_w = (d/dt)\left(\phi b_w S_w\right) \quad (5)$$

where ∇ is the gradient operator; $\nabla\cdot$ is the divergence operator; subscripts g and w stand for the gas phase and water phases, respectively; $M_n = k k_{rn}/\mu_n$ (n is gas or water) is phase mobility, where k, k_{rn}, and μ_n are the absolute permeability, relative permeability, and viscosity, respectively, and p is pressure; $\gamma_n = \rho_n g$ is the gas or water gravity gradient, where ρ_n is the phase mass density and g is gravitational acceleration; S_n is the degree of saturation; $b_n = 1/B_n$ is the gas or water shrinkage factor, where B_n is the formation volume factor; t is time; Z is elevation; Φ is the effective fracture porosity; q_g and q_w are the normal well source terms for gas and water, respectively; R_{sw} is the gas solubility in water; and q_m is the diffusion and desorption of gas between the matrix and the cleat, and is given in Eq. (9).

Gas phase pressure P_g and water phase pressure P_w are related by capillary pressure P_c, as expressed in the following equation:

$$P_c = P_g - P_w \quad (6)$$

Water and gas saturation satisfies the following equation:

$$S_w + S_g = 1. \quad (7)$$

Equations (4–7) make up four equations and contain four unknown variables, P_g, P_w, S_g, and S_w, hence, it is a solvable system.

As the simulator is a two-phase flow (water and gas), the relative permeabilities of gas and water satisfy $0 \le k_{rg} \le 1$ and $0 \le k_{rw} \le 1$. The volume of adsorbed gas in the coal matrix is described by the Langmuir adsorption isotherms (Eq. 8):

$$C(p) = \frac{V_L p}{P_L + p} \quad (8)$$

where V is the volume of gas adsorbed at pressure P and V_L and P_L are the Langmuir volume and Langmuir pressure, respectively.

The gas flow through the matrix is described mathematically by Fick's first law of diffusion, expressed in Eq. (9):

$$q_m = \left(\frac{V_m}{\tau}\right)[C - C(p)]z \quad (9)$$

where C is the average matrix gas concentration, V_m is the bulk volume of a matrix element, p is gas pressure, and τ is the sorption time.

The stress redistribution in coal results in the change of effective stress, and this leads to the change in the permeability of coal, as shown in Eq. 10 in the simulator:

$$k = k_0 e^{-\beta \Delta J_1'} \quad (10)$$

where k is the permeability, k_0 is the permeability with effective stress, β is a constant determined by laboratory tests, and $\Delta J_1'$ is the first stress invariant and is calculated as follows:

$$\Delta J_1' = \frac{\Delta\sigma_1' + \Delta\sigma_2' + \Delta\sigma_3'}{3} \quad (11)$$

The newly updated permeability is transferred with the coupling modules from FLAC3D to COMET3 in the flow calculation of gas and water, COMET3 is employed to simulate gas and water flow in coal, and the coupling modules transfer the pore pressure from COMET3 to FLAC3D as an external load and are used in the stress analysis.

It is worth noting that, in COMET3, the face drainage at and near the working face is modeled by two terms: q_g and q_w in Eqs. (4) and (5), representing the well flowrates for gas and water, respectively. These two terms can be calculated using Eq. (12):

$$q_n = WC\left(k_{rn} s_n/\mu_n\right)\left(p_{ijk} - p_{well}\right) \quad (12)$$

where n is gas or water, i.e., g and w, $p_{ijk} - p_{well}$ is the pressure difference between the average grid block pressure and the bottom well pressure, and WC is the well constant. A single well is modeled by a centrally located well of an equivalent radius within a rectangular grid block. The excavation process in this study was modeled by gradually placing more parallel wells in the grid blocks.

3 A Base Model

As most outbursts have occurred in roadway headings excavated during coal mining development, a simple model was set up to simulate the effect of a number of major parameters on the outburst mechanism during the roadway development in a coal seam, as shown in Fig. 1. The left side of the figure shows that a coal seam is sandwiched by two layers of rocks (roof and floor strata), and the right side is the model of a coal seam. The roadway is 5 m wide, 3 m high, and its advance was modeled in uniform steps of 15 m per shift.

There are many parameters contributing to outburst initiation. In this study, five major recognized parameters were investigated, including gas content, coal strength, mining depth, permeability of coal, and parameters characterizing gas adsorption in coal. Table 1 shows the

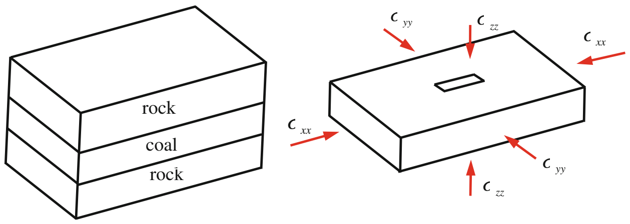

Fig. 1 Computational model

assigned values of the parameters used in this study. The assigned values for each parameter are based on normal coal mining conditions.

Among these parameters, the gas content is arguably the most important parameter in determining outburst proneness. It is observed that, unless the gas content reaches a critical level, an outburst will not manifest itself at all. The gas content is vitally important and is used as an outburst prone index in major coal-producing countries such as Australia and China.

In this numerical analysis, the input value of the initial gas content, which is linked to the initial gas pressure through the Langmuir adsorption isotherm (Eq. 8) and can be output by COMET3, is gradually increased for each combination of the other parameters, except for the gas content, until it reaches a critical value at which outburst occurs. At this point, one issue which needs to be addressed is how to define outburst initiation in the model. Since FLAC3D code is a finite difference code based on continuum media, it provides no mechanism to directly break down the grids. Therefore, no explicit mechanism of fracture and fragmentation of coal is included in this simulator. However, a direct and simple way to determine whether or not an outburst occurs is through a deformation criterion of the grids: if "large" deformation (0.5 m in this study) is formed after an excavation, an outburst is supposed to have occurred. At each time step, the output of maximum deformation of all grids is identified to determine if the deformation exceeds the criterion. The critical gas content value leading to an outburst is referred to as the gas content threshold value (THV). In other words, if the gas content in a coal seam exceeds the THV, the seam is considered to be outburst prone and preventive measures need to be taken to reduce the gas content to below the THV.

Table 1 Parameters and their values investigated

Parameter	Value	Unit
Gas content in coal	Initial value of 0.1	m^3/ton
Mining depth	200, 400, 600, 800, 1,000, 1,200	m
Coal strength (UCS)	2, 4, 6, 8, 10, 12	MPa
Horizontal permeability	0.001, 0.005, 0.01, 0.05, 0.1. 0.5, 1.0	md
Langmuir pressure	775, 860, 900, 1,000, 1,100, 1,200	kPa
Langmuir volume	11, 13, 15.5, 17, 19, 21	m^3/ton

4 Simulation Results and Discussions

4.1 The Effects of Coal Strength

The uniaxial compressive strength (UCS), the most commonly used coal strength index, is selected to represent coal strength in this study. In this study, the Mohr–Coulomb elastic-plasticity model was used. Coal failure may manifest itself as plastic deformation, a result of distributed damage evolution. The material properties were assigned in the following way: for different values of UCS, the same bulk modulus, shear modulus, and angle of internal friction were used, but cohesion and tensile strength were proportional to the UCS. Six different UCS values (2, 4, 6, 8, 10, and 12 MPa) were selected to investigate the effects of coal strength on the THV of the gas content. The simulated results are shown in Fig. 2. The results show that the THV increases with the UCS for each mining depth. For example, at a mining depth of 600 m, the THV increased from 5.3 to 9.3 m^3/ton as the coal UCS increased from 2 to 12 MPa, an increase of 1.8 times or a linear gradient of 0.4 m^3/ton/MPa. This clearly indicates the profound importance of coal UCS on the THV or outburst initiation. Furthermore, the results reveal that the THV decreases more significantly when coal UCS is low. For example, at a mining depth of 600 m, the THV decreased from 8.1 to 5.3 m^3/ton as the coal UCS reduced from 6 to 2 MPa, indicating that outburst is more sensitive to coal with a UCS of low value.

4.2 The Effects of Mining Depth

As some underground coal mines are extracting coal seams more than 1,000 m below the ground surface, six different mining depths, ranging from 200 to 1,200 m, were selected to investigate the effects of mining depth on the THV of gas content. The simulated results are shown in Fig. 3. The results show that the THV decreases with mining depth. For example, for coal UCS of 6 MPa, the THV reduced from 9.3 to 7.0 m^3/ton as the mining depth increased from 200 to 1,200 m, a reduction of 25 %. Moreover, the results reveal that the THV decreases more significantly with the increase in mining depth as the UCS is small. For example, for coal UCS of 2 MPa, the THV dropped from 6.5 to 2.0 m^3/ton when the mining depth increased from 200 to 1,200 m, a reduction of 69 %, indicating that coal of a low UCS value is more prone to outburst as the mining depth increases.

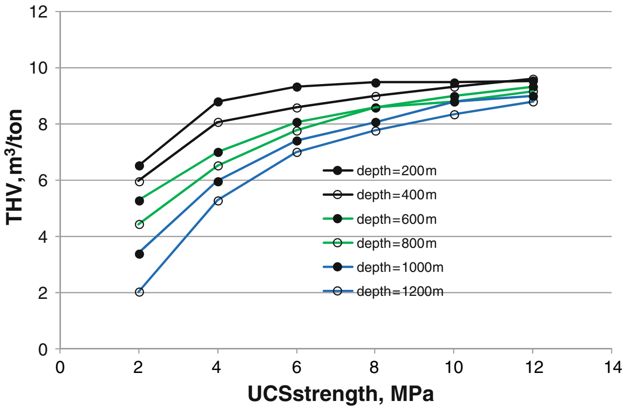

Fig. 2 Effect of coal uniaxial compressive strength (UCS) on the threshold value (THV) of gas content

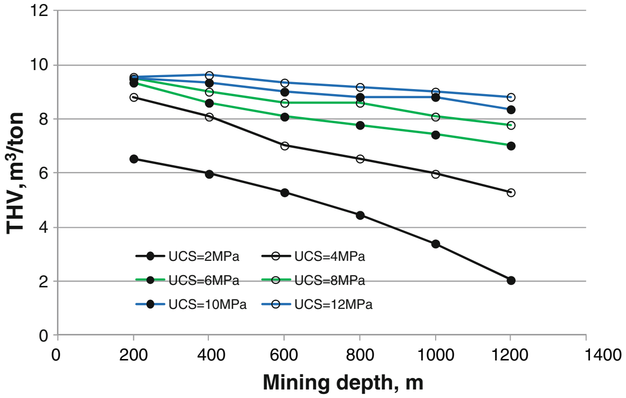

Fig. 3 Effect of mining depth on the THV of gas content

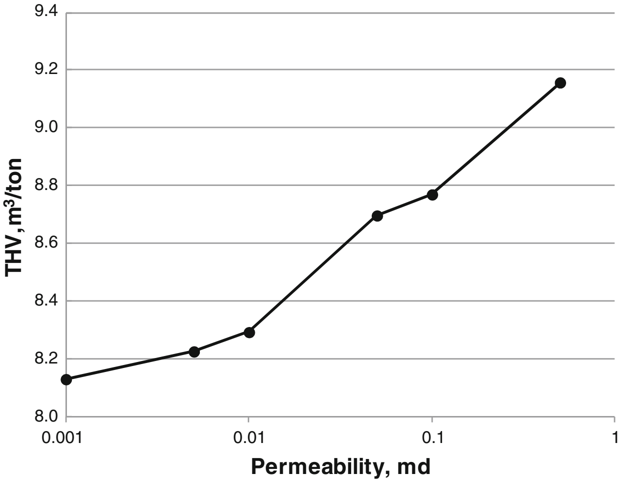

Fig. 4 Effect of permeability on the THV of gas content

4.3 The Effects of Coal Permeability

As the coal seam permeability varies greatly and, in general, the vertical permeability (K_v) of a coal seam is lower than its horizontal permeability (K_h), a range of 0.001 to 1 md for K_h is used with a ratio of K_v/K_h set as 10 in this numerical simulation. The simulated results are shown in Fig. 4. The results show that the THV increases with seam permeability. For example, the THV increased from 8.1 to 9.5 m^3/ton as the seam permeability increased from 0.001 to 1 md, an increase of 17 %, indicating that coal of low permeability is more prone to outburst.

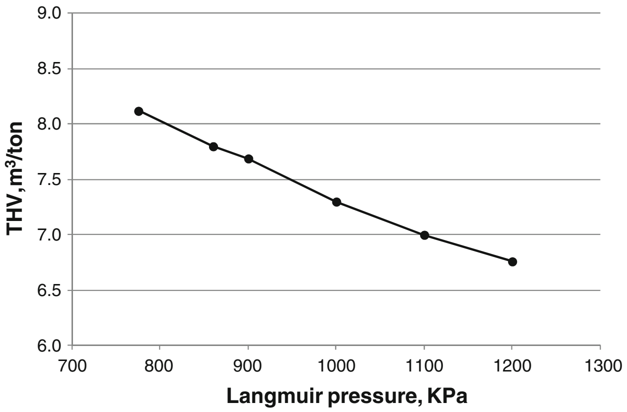

Fig. 5 Effect of Langmuir pressure on the THV of gas content

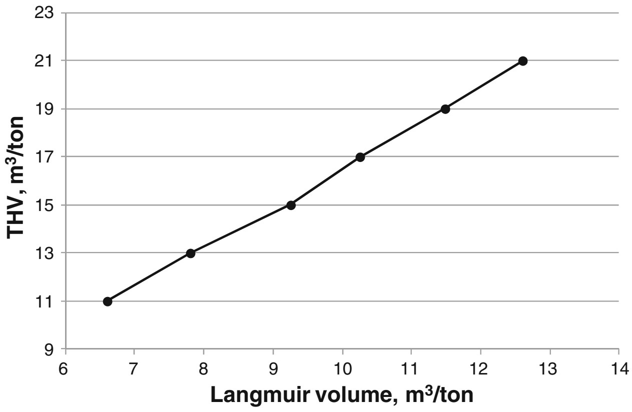

Fig. 6 Effect of Langmuir volume on the THV of gas content

4.4 The Effects of Langmuir Parameters on the Threshold Gas Content

The gas adsorption characteristics in coal can be described with the Langmuir pressure (P_L) and the Langmuir volume (V_L). A number of different values of Langmuir pressure (from 775 to 1,200 kPa) and Langmuir volume (from 6.6 to 12.6 m^3/ton) were selected to investigate the effects of gas adsorption in coal on the THV of gas content. The results show that, for the same V_L (13 m^3/ton in this case), a large P_L value resulted in a small gas content threshold (Fig. 5). And if P_L remained constant (777 kPa in this simulation), a small V_L value led to a small gas content threshold (Fig. 6).

5 Conclusions

The parametric studies reported in this paper were carried out with a newly developed coupled numerical simulator to investigate the effects of some major factors contributing to the initiation of outburst of coal and gas. When the gas content in coal is used as an outburst risk index, the results from this study show that the outburst risk for a coal seam increases under the following conditions: low coal strength, increased mining depth, low permeability, high Langmuir pressure, and low Langmuir volume. The modeled results are in agreement with field observations (Hargraves 1995; Lama and Bodziony 1998).

The results from this numerical investigation clearly show that the outburst risk of mining a coal seam depends on its mining and depositional conditions, implying that, even for the same coal seam, it may not be appropriate to use a single threshold value of gas content as an outburst risk index, as practiced currently in some coal mines in China and Australia.

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