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Model development and simulation study of the feasibility of enhancing gas drainage efficiency through nitrogen injection

Ting Ren [a], Gongda Wang [b,a,*], Yuanping Cheng [c], Qingxin Qi [b]

[a] School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, New South Wales 2500, Australia
[b] Mine Safety Technology Branch, China Coal Research Institute, 100013 Beijing, China
[c] School of Safety Engineering, China University of Mining and Technology, Xuzhou, China

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ABSTRACT

Pre-gas drainage plays a significant role in the prevention of coal and gas outburst in underground coal mines. However, difficulties of reducing the content of coal seam gas, especially localized coal seam CO_2, to be below threshold values within a given drainage lead time have been encountered in numerous coal mines in Australia. As the proneness of nitrogen outburst is way smaller than CO_2 or methane outburst, nitrogen injection would be an attractive technology for the underground gas drainage management if it is really able to enhance the drainage efficiency. From this point of view, this paper aims at investigating the feasibility of implementing this technology in Bulli seam, Sydney Basin through numerical modelling.

Four parts of work were conducted in this paper. Firstly, a binary gas transport model was developed through analysing the binary gas transport mechanism in both coal matrix and coal cleat, and also the matrix-cleat interaction due to binary gas sorption swelling. A real gas mixture viscosity was introduced and its change depends on the molar fractions of both components and their own viscosities. Secondly, the characteristics of the Bulli seam were studied to collect the parameters required by the binary gas transport model. Through laboratory experiment, field investigation and reviewing literature, the coal seam gas (methane, CO_2) and nitrogen adsorption and diffusion properties, in-situ seam properties such as permeability, porosity, cleat spacing and virgin pressure are either measured or estimated. Thirdly, the regular drainage effects in six scenarios with different initial permeability and coal seam gas type were examined and three of them are found to have drainage difficulties, i.e., the moderate permeability (0.5 mD) CO_2 case, the low permeability (0.005 mD) methane case and the low permeability (0.005 mD) CO_2 case. The effects of nitrogen injection on enhancing gas drainage efficiency, especially reducing the gas content, are studied for these scenarios. Results show that a satisfactory result is obtained for the moderate permeability CO_2 case, the CO_2 content can be reduced largely and an apparent increase of CO_2 production rate can be seen. However, the effect of nitrogen injection in low permeability methane scenario is even worse than the regular drainage using two boreholes, although it can increase the methane flow rate of single borehole. For low permeability CO_2 case, nitrogen injection can accelerate the reduction ratio of CO_2 content in part of the injection area and increase the total CO_2 flow rate, but the enhanced effect is limited and the CO_2 content is still high after 12 months of injection. Last but not least, the feature of the movement of coal seam gas content peak in the injection area is discussed and the reasons inducing the different injection effects between methane and CO_2 scenarios are analysed. A combination of lateral movement and drop of coal seam gas content peak is found, and permeability is believed to have great impacts on the movement speed. There is no sign indicating either diffusion or permeability change controls the different injection effects between methane and CO_2 scenarios, while the different competitive adsorption characteristics and the increase of mixture gas viscosities may have influences on this difference.

1. Introduction

Coal and gas outburst rapidly releases a large quantity of gas in conjunction with the injection of coal into the working face in underground coal mines. This sudden and violent nature of the

* Corresponding author at: School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, New South Wales 2500, Australia.
E-mail address: wgdcumt@gmail.com (G. Wang).

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outburst poses huge threats to the safety of miners and mine facilities, and its prediction and prevention is a major concern of the underground mine operation [1]. Global experiences show that two gases are predominately associated with coal and gas outburst, i.e., methane and CO_2. Methane is generated during the coalification process and is the main type of coal seam gas. CO_2 may originate from coal maturation, oxidation and magmatic activity, dissolution of carbonate minerals [2,3], and the CO_2 related outburst accidents have been occurred in Australia, Canada, China, Czech Republic, France, Poland and Turkey [4–7]. The precise mechanism of gas outburst is still mysteries due to its complexity, but it is generally accepted that two conditions, i.e., coal failure and especially high gas pressure/content, must be met for the outburst to occur [1]. Since mining of seams liable to gas outburst requires specific procedures to ensure that the proneness of outburst has been eliminated, gas content often becomes a critical index of outburst proneness due to its reliability and convenience of measurement.

To allow normal mining activities to take place in a safe and timely manner, pre-gas drainage using in-seam boreholes has played a critical role in reducing high in-situ gas content [8]. However, difficulties of reducing gas content below threshold values within a given drainage lead time have been encountered in numerous coal mines in Bowen Basin and Sydney Basin of Australia. Preliminary discussion indicates these difficulties are possibly related to localized regions of low permeability and rich of CO_2 composition [9], which lead to requiring extended drainage time. In addition, changes in mine development schedules may need accelerated drainage, and reducing residual gas levels to low levels is also beneficial for mitigation of frictional ignitions and fugitive emissions [10]. A technology of enhancing underground gas drainage efficiency and reducing residual gas content is demanded.

Using CO_2 or flue gas as an injectant to enhance coalbed methane (CBM) recovery has been proven as an effective method and discussed extensively before [11–13]. However, it is unacceptable for the underground gas drainage as CO_2 has already been identified as an outburst gas. Because the proneness of nitrogen outburst is much smaller than CO_2 outburst, the use of nitrogen as an injectant does not introduce a similar risk and thus arises to be an attractive option of enhancing underground gas drainage efficiency [14]. Several field trials of enhanced coalbed methane recovery (ECBM) involving nitrogen injection have been documented, such as the Tiffany unit trial [15], the Alberta Fenn Big Valley micro pilot trial [16], the Sydney Basin trial [17] and an underground trial in China [18]. The underground trial demonstrated a 2-fold of methane flow while the reduction of gas content was not obvious (from 9.77 m^3/t to 8.68 m^3/t). As this trial adopted a small borehole spacing (from 0.7 m to 1.5 m), short borehole depth (15 m) and low injection pressure (0.5 MPa), the results seems not to be indicative for predicting the nitrogen injection effect in other underground scenarios.

Several publications discussing the mathematical model of binary gas transport in coal seam are available. For example, Wu et al. [19] developed a dual poroelastic model for CO_2 enhanced coalbed methane recovery. Xia et al. [20] used a coupled compositional (coal seam gas and air) model to investigate the influence of borehole sealing on gas drainage effect. Kumar et al. [21] studied the CO_2 injection effect on heterogeneously permeable coalbed reservoirs, a coupled finite element (FE) model was developed. In general, these studies provide useful theoretical foundations but a fully coupled model needs to be further developed as: the viscosity of gas mixture was treated as constant before, while it is actually change with each gas composition; gas diffusion coefficient is easily determined and extensively used comparing to matrix permeability, however it was not used to calculate the gas exchange rate between matrix and cleat [19–21]; the extended Langmuir model was incorrectly written in some studies [19,21]. In the present paper, a fully coupled binary gas transport model is developed and its differences with the published models are discussed. The characteristics of Bulli seam, Sydney Basin are analysed and the parameters required by the binary gas transport model are collected from both experimental and flied data. Based on the developed model and the gained parameters, the feasibility of using nitrogen injection to enhance gas drainage efficiency is studied through numerical simulation.

2. Model development of binary gas transport

2.1. Free gas and adsorbed gas

According to Dalton's law, the pressure (Pa) of a binary mixture of non-reactive gases in coal cleat and matrix can be defined as:

$$p_m = p_{m1} + p_{m2} \tag{1}$$

$$p_f = p_{f1} + p_{f2} \tag{2}$$

where the subscripts m and f denote coal matrix and coal cleat, respectively, the coal seam gas is defined as component 1 and the injected nitrogen is defined as component 2. The ideal gas law gives the relationship between gas pressure and molar density (mol/m^3) for each component:

$$C_i = \frac{n_i}{V} = \frac{p_i}{RT} \tag{3}$$

where C_i is gas molar density, n is gas moles (mol), V is the free volume occupied by the binary gas (m^3), R is the gas constant (m^3 Pa/(K mol)), T is temperature (K). Assuming the gas adsorption obeys Langmuir relationship:

$$V_t = \frac{V_L b p_m}{1 + b p_m} \tag{4}$$

where V_t is the total adsorbed gas volume (m^3), $b = 1/P_L$ (1/Pa) and V_L (m^3/kg) are the Langmuir constants. Substituting Eq. (1) into Eq. (4) yields the extended Langmuir model:

$$V_t = \frac{V_{L1} b_1 p_{m1} + V_{L2} b_2 p_{m2}}{1 + b_1 p_{m1} + b_2 p_{m2}} \tag{5}$$

An extensively used assumption between gas content of sorption and the behaviour of matrix swelling is the linear relationship [22–24]. By analogy, the total adsorption induced volumetric strain of a binary gas can be expressed as:

$$\varepsilon_s = \frac{\sum \varepsilon_{Li} b_i p_{mi}}{1 + \sum b_i p_{mi}} \tag{6}$$

where ε_L is the Langmuir-type strain coefficient (dimensionless).

2.2. Gas transport in matrix

Diffusion in the coal matrix is driven by the concentration gradient and obeys the Fick's law. The gas exchange rate Q_s of each gas can thus be expressed as [25,26]:

$$Q_{si} = -D_i \sigma \frac{M_i}{RT}(p_{mi} - p_{fi}) \tag{7}$$

where D is the diffusion coefficient (m^2/s), σ is the shape factor of cubic coal matrix blocks (1/m^2) and can be obtained from [27]:

$$\sigma = \frac{3\pi^2}{L^2} \tag{8}$$

where L is the cleat spacing (m). The mass of each gas contained in the matrix of a unit volume of coal can be defined as the summation of the adsorbed gas and free gas:

$$m_{mi} = \phi_m p_{mi} \frac{M_i}{RT} + \rho_c \rho_{gsi} \frac{V_{Li} b_i p_{mi}}{1 + \sum b_i p_{mi}} \tag{9}$$