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A Numerical Evaluation of Coal Seam Permeability Derived from Borehole Gas Flow Rate

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Abstract: Coal seam permeability is a critical factor in coal seam gas extraction and gas outburst control. In Australian coal mines, coal seam permeability is normally estimated using a packer test or drill stem test. In contrast, Chinese coal mines generally estimate a parameter called the “gas conductivity coefficient” by measuring natural gas flow rates from an underground borehole drilled through a coal seam. With this method, it has been frequently reported that the permeability of many Chinese coal seams is between 0.0001 mD and 0.01 mD, which is extremely low compared to that of Australian coal seams (1–100 mD). It is therefore natural to wonder how closely the Chinese method measures permeability. Resolving this question will allow knowledge and experience in outburst management to be shared between Australian and Chinese coal mines. This question is investigated by the numerical modelling of gas desorption and flow through a seam of known permeability and by using the model’s borehole gas flow rate to estimate the permeability using the Chinese method. A total of 126 simulations were run with various input reservoir parameters. The results suggest that the Chinese method estimates permeability at an accuracy of 85% to 100%, which is adequate for mine pre-drainage design and outburst control. For the high diffusion rate (e.g., high gas content and short desorption time) and low Darcy flow rates (e.g., low permeability), these errors are reduced.

Keywords: permeability; numerical simulation; borehole radial flow; gas conductivity coefficient; outburst



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1. Introduction

The permeability of coal seams is an intrinsic quantity, quantifying the ease of fluid flow through the coal. It is a critical factor in determining the efficiency of gas extraction from coal seams for coal seam gas development and coal mine gas drainage [1–3]. It is also an important parameter to assess and control the risk of outburst [4,5], which refers to a sudden and violent injection of gas and coal/rock materials from underground coal working faces.

Coal seam permeability may be inferred using a number of experimental methods, such as the drill stem test (DST) [1,6,7], packer test [8,9], and slug test [1,10,11]. These methods generally involve measuring the water pressure (or water head) and flow rate response during the controlled injection into, or withdrawal from, an isolated section of a borehole drilled from the ground surface. The hydraulic conductivity, and hence the permeability of a coal seam, can be estimated from the testing data. These types of methods are commonly used in Australia [1,6–8] and some other countries, such as the USA [1,9,10] and Poland [11].

In contrast, the underground borehole gas flow test [12–16], which involves measuring the natural flow rate of gas (desorbed from coal) into a testing borehole drilled through the entire cross-section of the seam, is used in Chinese coal mines to infer coal seam permeability. The method estimates a parameter called the gas conductivity coefficient (GCC) of coal (though some literature refers to it as the permeability coefficient of coal). The GCC can be interpreted as the volume of gas that flows through one square meter of

coalface of one-meter length within a day under certain pressure conditions explained fully below. When converting to permeability, the GCC of $1 \text{ m}^2/(\text{MPa}^2 \text{ day})$ corresponds to approximately $2.5 \times 10^{-17} \text{ m}^2$ (0.025 mD) of the permeability [16].

The method of the GCC measurement and analysis, normally referred to as the borehole radial flow (BRF) method in China, was developed by Zhou [17,18] and is based on the approximate piecewise solution of a two-dimensional single-phase planar transient radial flow of gas towards a borehole through a porous coal seam. The approximate solution was obtained by numerical simulations and the similarity technique. Sun et al. [19] found that the approximate solution can encounter situations of no solution existing or two solutions existing, in some cases, due to a discontinuity at the intersections of the piecewise segments. Despite this shortcoming, the BRF method has been widely used in China since 1980 and has become a standard method of estimating coal seam permeability for the coal mining industry [20]. Jiang [21] reported that the BRF method has higher accuracy than other borehole gas measurement-based methods, including the Marconi gas pressure method, the Krichevsky gas pressure method, and the Krichevsky gas flow quantity method.

With this method, it has been frequently reported that the coal seam permeability in Chinese coal seams is mostly between 0.0001 mD and 0.01 mD [22], which is extremely low in comparison to Australian coal seam permeabilities, which typically range between 1–100 mD [23,24]. The 2D solution used in the method may or may not describe the reality because the idealised models ignore potentially important phenomena, such as gas desorption during the days of observation. Therefore, it is natural to wonder how accurately the method predicts permeability. Resolving this question will allow knowledge and experience in outburst management and gas pre-drainage to be shared between Australian and Chinese coal mines.

In recent years, numerical modelling has been used as an approach to investigate the effect of BRF's assumptions and operational parameters on the accuracy of the method [25–27]. Liu et al. [25] assessed two assumptions of the BRF method, i.e., the single porosity model and the parabolic expression of gas content and gas pressure, by comparing the gas pressure distribution and borehole gas flow rate. They reported that the coal permeability inferred by the BRF method is always smaller than the actual value and that coal seams with large cleat spacing or high Langmuir volume will lead to very low accuracy. Lin et al. [26] investigated the parameters affecting the accuracy of the BRF method by employing a finite volume flow method to simulate the borehole gas flow rate. They used a golden section search method to match numerically calculated the borehole flow rate under a different GCC to the measured borehole flow rate. The model input GCC that results in the best match is taken as the GCC of the coal seam. With this method, they found that the initial gas pressure and the borehole radius are the key factors that affect the prediction of coal seam permeability.

In this paper, the BRF method is further investigated by using a numerical model with a focus on quantifying how closely the Chinese standard BRF method predicts coal seam permeability. The purpose of this quantification is to facilitate a comparison of the differences and adaptability of an outburst risk assessment and gas pre-drainage technologies between China and Australia. The numerical model involves a horizontal coal seam of uniform thickness, with a hole at its centre representing the borehole. A permeability and an initial gas content are prescribed to the model. Single-phase flow is used, along with gas desorption from the coal matrix. The model is initialised to a pore pressure corresponding to the initial gas content, and the gas flow rate from the borehole is measured. Using the synthetic data, the Chinese BRF method is used to infer coal permeability, and the results are compared with the known permeability prescribed to the model.

2. The Methodology of Measuring GCC

2.1. Fundamentals of GCC

The flow of gas in a porous coal seam is considered the laminar flow (Figure 1) and obeys Darcy's law. The velocity u (m/s) of gas is given by:

$$u = -\frac{k}{\mu} \cdot \frac{dp}{dl} \quad (1)$$

where k is the permeability of the coal seam (m^2), which varies in different types and structures of coal, μ is the dynamic viscosity of the gas ($\text{Pa} \cdot \text{s}$), and dp/dl is the pressure gradient in the direction of flowing (Pa/m). The value of this velocity can also be treated as the volume of gas passing through a unit area of A (m^2), perpendicular to the flowing direction within the unit time. This is the flow rate, q_p (m^3/s), at the pressure, p , through the area:

$$q_p = uA = -A \cdot \frac{k}{\mu} \cdot \frac{dp}{dl} \quad (2)$$

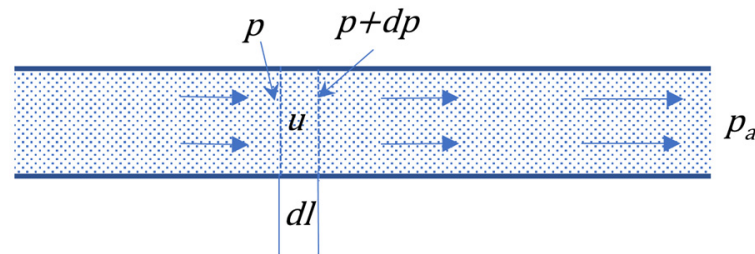


Figure 1. Laminar flow of gas in a coal seam.

As gas is compressible, the gas flow rate varies with the changing pressure along the path of the flow. The gas flow rate is often measured and expressed in standard temperature and pressure. Assuming the temperature in the seam does not change, and applying the Boyle's law to the flow rate, q_p , at the pressure, p , and the flow rate, q , at the atmosphere pressure, p_a :

$$pq_p = p_a q \quad (3)$$

The flow rate at the atmosphere pressure is:

$$q = q_p \frac{p}{p_a} = -A \cdot \frac{k}{2\mu p_a} \frac{d\bar{P}}{dl} = -A \cdot \lambda \cdot \frac{d\bar{P}}{dl} \quad (4)$$

where $\bar{P} = p^2$ and

$$\lambda = \frac{k}{2\mu p_a} \quad (5)$$

is the so-called *gas conductivity coefficient* (GCC) of the coal ($\text{m}^2/(\text{Pa}^2 \cdot \text{s})$). The GCC, λ , relates to the permeability of coal, the dynamic viscosity of the gas, and the atmospheric pressure. Some literature, for example, Liu et al. [25], have translated the GCC as the permeability coefficient. However, as it contains the flowing properties of the gas, it is more proper to call it the gas conductivity coefficient of coal.

In practice, the unit of the GCC is often converted to $\text{m}^2/(\text{MPa}^2 \cdot \text{day})$. Applying $\mu = 1.05 \times 10^{-5} \text{ Pa} \cdot \text{s}$ and $p_a = 101,325 \text{ Pa}$, the permeability, k , equivalent to $\lambda = 1 \text{ m}^2/(\text{MPa}^2 \cdot \text{day})$, can be calculated as:

$$k = 2\lambda\mu p_a = 2 \times 1 \frac{\text{m}^2}{\text{MPa}^2 \cdot \text{day}} \times 1.05 \times 10^{-5} \text{ Pa} \cdot \text{s} \times 101325 \text{ Pa} \approx 2.5 \times 10^{-17} \text{ m}^2. \quad (6)$$

2.2. Estimating GCC by the Borehole Radial Flow (BRF) Method

According to Equation (4), the GCC of coal, which varies in different coal seams, can be estimated by measuring the flow rate of gas desorbed from coal and flowing into a borehole. Three different methods can be used: (1) the radial flow into a borehole, (2) the spherical flow into a borehole, and (3) the linear flow into a roadway. Of them, the borehole radial flow (BRF) method is the most popular one and has been set as the coal industry standard in China [20].

The BRF method is based on the solution of the planar radial flow of gas into a borehole drilled perpendicularly to and through the coal seam (Figure 2). Details of the method can be found in Zhou and Lin [16]. To better understand the method, a brief description is given here.

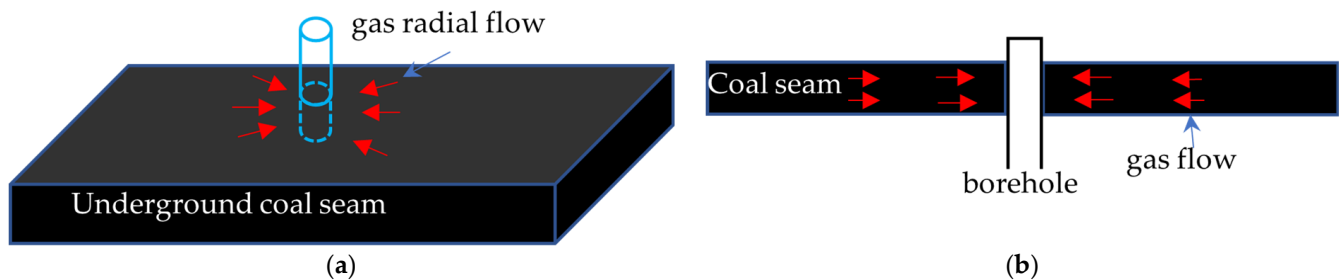


Figure 2. Illustration of gas radial flow around a borehole through a coal seam: (a) oblique view; (b) cross-section view.

The BRF method has the following assumptions:

- The single-phase (gas) flow is considered; the gas behaves as an ideal gas, and the gas flow is laminar.
- Only the Darcy flow along the macropores/cleats is considered. The gas desorption and diffusion rate is assumed to dominate the Darcy flow and is therefore excluded.
- The gas content and gas pressure have a parabolic relationship and are expressed by the gas content coefficient, α : $Q = \alpha \sqrt{p_0}$. (This relationship is commonly expressed by the Langmuir formula).
- The roof and floor of the coal seam are impervious rock layers and do not contain gas.
- The gas flow in the coal seam is isothermal.
- The permeability of the coal seam is not impacted by gas desorption from the coal matrix.

Applying the expression in Equation (4) to the continuity equation of the gas in the radial flow (Figure 2), Zhou and Lin [16] presented the governing partial differential equation,

$$\frac{\partial \bar{P}}{\partial t} = \frac{4\lambda \bar{P}^{-3/4}}{\alpha} \left(\frac{\partial^2 \bar{P}}{\partial r^2} + \frac{1}{r} \frac{\partial \bar{P}}{\partial r} \right). \quad (7)$$

This is a non-linear second-order equation, and its exact analytical solution cannot be obtained. Instead, with numerical solutions for various parameters and the similarity theory, Zhou and Lin [16] presented a piecewise approximate relationship between the dimensionless flow rate, Y , and the dimensionless time, F_0 ,

$$Y = a F_0^{-b} \quad (8)$$

where

$$Y = \frac{\bar{q} R}{\lambda (p_0^2 - p_1^2)} = \frac{A}{\lambda}, \quad F_0 = \frac{4\lambda t p_0^{1.5}}{\alpha R^2} = B \lambda \quad (9)$$

and the regression constants, a and b , have different values within different time ranges. A and B are defined in Equation (9); p_0 and p_1 are the *in situ* gas pressure in the coal seam and the pressure in the borehole (generally taken as the atmosphere pressure), respectively,

with a unit of MPa; t is the time (days) when the flow rate is measured since the sealing valve is opened; R is the radius of the borehole with a unit of m; α ($\text{m}^3 / (\text{m}^3 \cdot \text{MPa}^{1/2})$) is the gas content coefficient. \bar{q} is the average of the gas flow rate through the unit area of the borehole surface and is given by the flow rate through the borehole surface, Q_f (m^3/day), at measuring time of t :

$$\bar{q} = \frac{Q_f}{2\pi R h} \quad (10)$$

where h is the thickness of the coal seam, with a unit of m.

Substituting Equation (9) into Equation (8), the following general expression for λ can be obtained:

$$\lambda = a' A^\beta B^\delta \quad (11)$$

where the new regression constants are $\beta = 1/(1-b)$, $\delta = b/(1-b) = \beta - 1$, and $a' = a^{-\beta}$. The values of these new constants at different time ranges are given in Table 1.

Table 1. The values of the regression constants in Equation (11) at different time ranges of F_0 (Zhou and Lin [16]).

F_0	a'	β	δ
10^{-2} –1.0	1.00	1.61	0.61
1.0–10	1.00	1.39	0.39
10 – 10^2	1.10	1.25	0.25
10^2 – 10^3	1.83	1.14	0.14
10^3 – 10^5	2.10	1.11	0.11
10^5 – 10^7	3.14	1.07	0.07

Since the ranges are given for F_0 , which depends on λ as in (9), the computed value of λ must be checked to satisfy the corresponding validity range of $F_0 = B\lambda$. It was suggested that for a short time t , those for the low value of F_0 could be used to check first, and for a long time, those for a high value of F_0 are checked first.

The calculation step can be summarised as follows:

- Use Equation (10) to calculate the average flow rate per day per unit area of the borehole surface, \bar{q} ;
- Calculate the gas content coefficient, α , with the known *in situ* gas content, Q , and the *in situ* gas pressure of the coal seam, p_0 ;
- Calculate A and B from Equation (8) with \bar{q} and t together with the *in situ* gas pressure, p_0 , in the coal seam, the pressure p_1 in the borehole, and the gas content coefficient, α .
- Calculate λ from Equation (11) with a set of regression constants.
- Calculate the value of $F_0 = B\lambda$. If the value is within the corresponding range, then the value of λ is chosen as the GCC of the seam for the measurement. If not, then calculate λ with another set of the regression constants. Repeat the calculation till the range is satisfied.

A simple example was given by Zhou and Lin [16]. The data of the example are: the borehole radius is $R = 0.05$ m; the thickness of the coal seam is $h = 3.5$ m; the *in situ* gas pressure is $p_0 = 4.0$ MPa; the pressure at the borehole is $p_1 = 0.1$ MPa; the gas content coefficient is $\alpha = 1.328 \text{ m}^3/(\text{m}^3 \cdot \text{MPa}^{1/2})$; the flow rate from the borehole measured on the 42nd day is $3.53 \text{ m}^3/\text{d}$. With these data, it was found that

$$A = 1.0 \times 10^{-2}, B = 3.95 \times 10^5$$

and $\lambda = 5.3 \times 10^{-2} \text{ m}^2/(\text{MPa}^2 \cdot \text{day})$. If the dynamic viscosity of methane is $1.05 \times 10^{-5} \text{ Pa} \cdot \text{s}$, then the permeability of the coal seam is $1.29 \times 10^{-18} \text{ m}^2$.

2.3. Field Measurement of Borehole Radial Gas Flow Rate

A general procedure is summarised below.

- Drill a borehole perpendicularly to and through the coal seam (Figure 3). Generally, the borehole is drilled from a roadway up into the coal seam.
- Seal the borehole and measure the *in situ* gas pressure, p_0 , in the coal seam. The duration of the gas pressure measurement can take 5~30 days, depending on the seam permeability, *in situ* gas pressure, and whether an inert gas is used to accelerate the measurement.
- Open the sealing valve so that the pressure in the borehole reduces to the ambient air pressure in the roadway.
- Measure the volume of the gas, Q_f , emitted naturally from the coal seam into the borehole after the sealing valve was opened. Usually, the gas flow rate is measured several times on different days until the flow rate becomes stable or a less than 10% difference in two measurement intervals (usually 24 h).

Estimate the GCC according to the method described in Section 2.2.

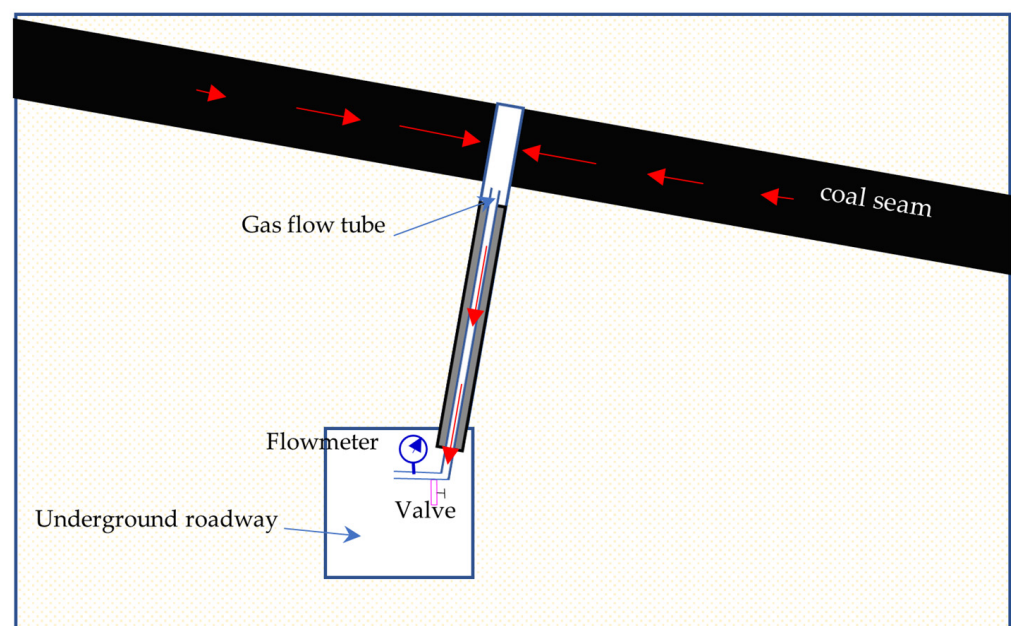


Figure 3. Schematic of the field configuration of the BRF method (modified from [20,25]). The seam gas pressure, which equals the critical desorption pressure of the seam, is first measured before opening the valve to measure the borehole gas flow rate.

3. The Numerical Model and Assumptions of Gas Flow in Coal Seam

3.1. Mathematical Models

We employed a numerical model for the gas radial flow into a borehole perpendicular to the coal seam to produce the gas flow rate in the borehole for checking the accuracy of the BRF method. The numerical model, as shown in Figure 4, involves a single, flat, horizontal coal seam of uniform thickness and large extent. The uniform thickness is the same as the assumption used in the Chinese method. The large extent of a 10 km radius is designed to minimise the boundary effect for high permeability simulation cases (no spurious effect from the models' boundary is seen in the modelling results).

The thickness of the seam is mostly irrelevant; for instance, doubling the thickness merely doubles the observed gas flow rate. Therefore, the flow rate is from the thickness of the unit length (m). The seam is pierced by a borehole of a radius of R , as shown in Figure 4. It is assumed that the coal has single porosity (as in the BRF method and with no distinguishment of the pore and cleats), and there is no water in the seam; so, the two-phase flow, water saturation, and the capillarity and relative permeability are not included. This assumption also reflects the field reservoir condition at the time of the

borehole flow rate measurement, which would be carried out after the 5~30 days of gas pressure measurement.

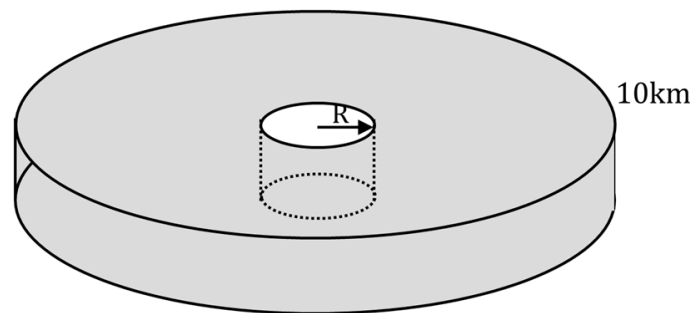


Figure 4. Model geometry: a single coal seam with a radius of 10 km is pierced by a borehole with a radius of R.

The gas flow is assumed to be governed by the conservation of mass, which is Darcy's equation augmented with the change in gas concentration:

$$\phi \frac{\partial p}{\partial t} + (1 - \phi) \frac{\partial C}{\partial t} = \nabla \cdot \left(\frac{\rho}{\mu} k \nabla p \right) \quad (12)$$

where ϕ is the coal porosity (dimensionless); C is the adsorbed gas concentration (kg/m^3); ρ is the gas density (kg/m^3); ∇ denotes the vector of the spatial derivatives $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$ (m^{-1}); other variables are as used previously.

The gas desorption, which is neglected in the assumptions of the BRF method, is considered in the numerical model. Gas stored in coal is mainly in the adsorbed state. The source of the gas flow in the borehole is due to the desorption governed by the Langmuir equation:

$$(1 - \phi) \frac{\partial C}{\partial t} = -\frac{1}{\tau} \left(C - \frac{\rho_L p}{P_L + p} \right) \quad (13)$$

where τ is the desorption time constant (s); ρ_L is the Langmuir density ($\text{kg}(\text{gas})/\text{m}^3$); P_L is the Langmuir pressure (Pa).

These equations are mass-based, rather than based on volumes. However, it is more conventional for engineers to work with gas volumes at a standard temperature and pressure rather than masses. For the conversion, it is assumed that the density of the gas at a standard temperature and pressure is

$$\rho_{STP} = 0.717 \text{ kg}/\text{m}^3. \quad (14)$$

The adsorbed gas concentration may also be quoted in $\text{m}^3(\text{gas})/\text{tonne}(\text{coal})$, and it is assumed here that the density of coal is

$$\rho_{\text{coal}} = 1.3 \text{ tonne}/\text{m}^3. \quad (15)$$

For the adsorbed gas concentration, \tilde{C} , given in the unit $\text{m}^3(\text{gas})/\text{tonne}(\text{coal})$, the numerical model will use $C = \tilde{C} \rho_{STP} \rho_{\text{coal}}$ (with units $\text{kg}(\text{gas})/\text{m}^3(\text{coal})$). For the Langmuir volume, V_L , given in $\text{m}^3(\text{gas})/\text{tonne}(\text{coal})$, the numerical model will use $\rho_L = V_L \rho_{STP} \rho_{\text{coal}}$ (with units $\text{kg}(\text{gas})/\text{m}^3(\text{coal})$).

3.2. Reservoir Parameters

The initial conditions for the adsorbed gas concentration are homogeneous and fixed as per Table 2, which shows the typical values of the parameters used in the numerical

simulations. The radius of the borehole is the typical value used in the Chinese guideline. The initial conditions for the gas pore pressure are homogeneous and equal to

$$P_{initial} = \frac{P_L C}{\rho_L - C} = \frac{P_L \tilde{C}}{V_L - \tilde{C}}. \quad (16)$$

This means that the pore space is fully saturated with gas, and any reduction of the gas pressure will result in gas being desorbed. The boundary conditions are zero fluid flux at the outer edge (10 km from the borehole) and the atmospheric pressure within the borehole.

Table 2. Values of parameters used in the numerical study.

Parameter	Value(s)	Notes
Borehole radius, R [m]	0.05	Typical small borehole size used in the Chinese method. This is typical of experiments performed in the field.
Simulation time [days]	20	
Coal porosity, ϕ	0.05, 0.1	Without gas desorption, time would scale with ϕ , meaning ϕ could be scaled out of the problem, but with desorption, this is not the case.
Coal permeability, k [m ²]	$10^{-12}, 10^{-13}, 10^{-14}, 10^{-15}, 10^{-16}, 10^{-17}, 10^{-18}$	Without gas desorption, permeability could be scaled out of the problem. For comparison with hydraulic (water flow) problems: 1Darcy $\approx 10^{-12}$ m ² ≈ 1 m·day ⁻¹ .
Desorption time constant, τ [days]	1, 10, 10 ⁶	The case of $\tau = \infty$ means that no desorption will occur.
Langmuir pressure, P_L [MPa]	1	Must be less than the Langmuir volume.
Langmuir volume, V_L [m ³ /tonne]	20	
Initial gas content, \tilde{C} [m ³ /tonne]	4, 8, 12	
Gas density and viscosity	Variable	A high-precision equation of state for methane is used, which is in contrast to the ideal gas assumption used in the Chinese method.
<i>In situ</i> temperature [K]	303	This impacts the gas density and viscosity through the equation of state. The temperature is assumed fixed.
Atmospheric pressure [kPa]	101	Assumed to be fixed.

3.3. Model Results

The above mathematical problem was solved with the finite element framework, MOOSE, for the multiphysics process [28,29]. The model is axially symmetric, and the physics are independent of the vertical position. Close to the borehole, the mesh elements have a size of 7 cm in the radial direction, and this size is increased with the distance from the borehole to become 600 m closer to the outer boundary. Figures 5 and 6 demonstrate some results of the model.

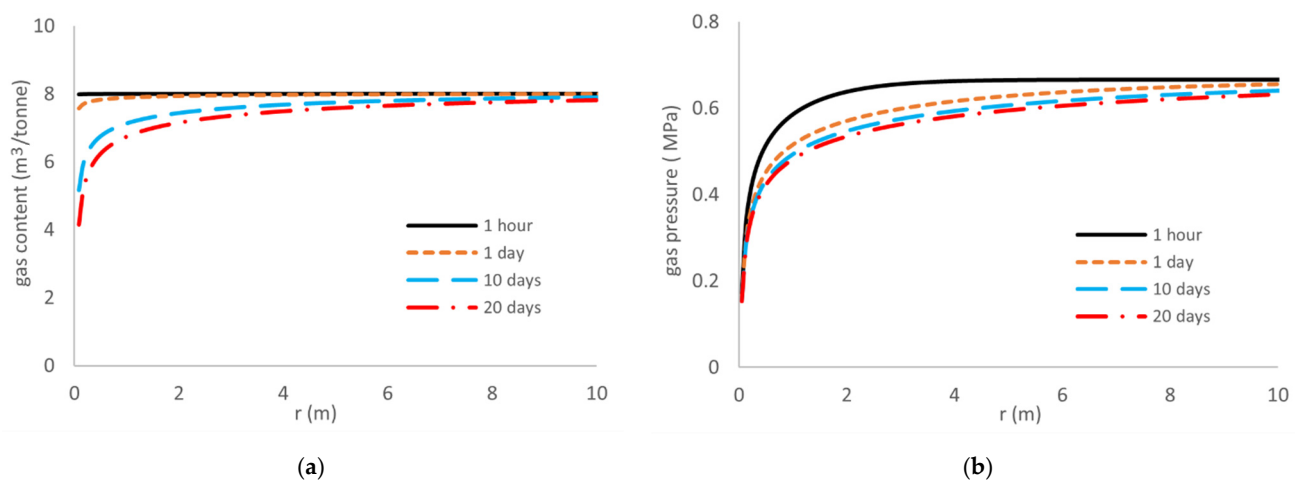


Figure 5. Radial distribution of (a) gas content and (b) gas pressure around the borehole at four different times.

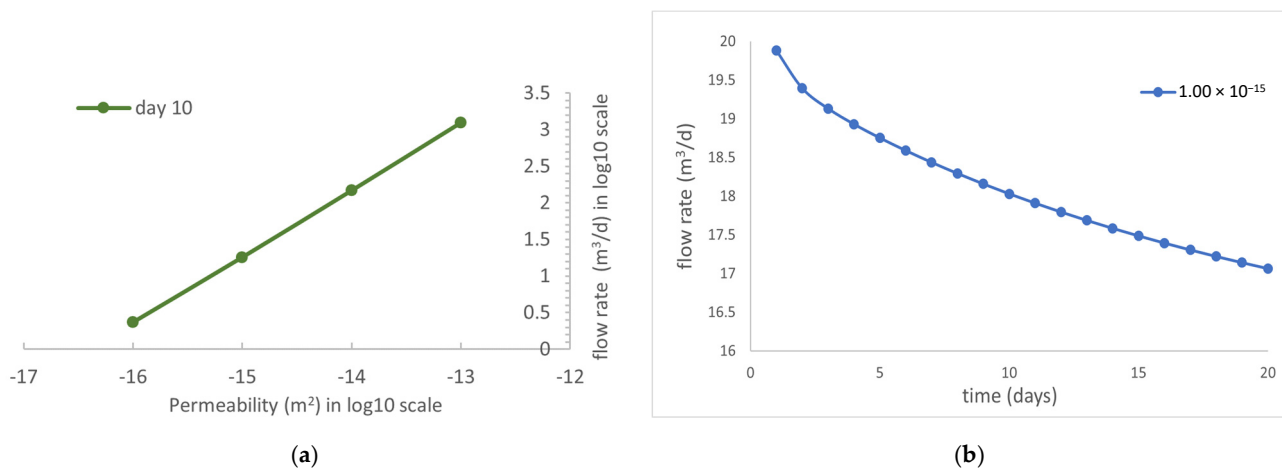


Figure 6. Variation of borehole flow rate with (a) permeability on day 10 and (b) time under a permeability of 10^{-15} m^2 .

Figure 5 shows the distributions of the gas content and pressure along a radial line at four time instants: 1 h, 1 day, 10 days, and 20 days. The input parameters for these cases are the desorption time constant = 10 days, *in situ* gas content = $8 \text{ m}^3/\text{tonne}$, porosity = 0.1, and the permeability = 10^{-15} m^2 . The results clearly show the drawdown effect of the gas drainage. The distribution patterns of the gas content and gas pressure around the drainage borehole and their evolution with time are consistent with the numerical modelling results conducted by other researchers [25,30,31].

Figure 6 shows variations of the gas flow rate in the borehole with different permeability values and time. Four permeability values are compared in Figure 6a: 10^{-16} m^2 , 10^{-15} m^2 , 10^{-14} m^2 , and 10^{-13} m^2 . The model shows that the gas flow rate in the borehole depends on the seam permeability: an increase of permeability by one order of magnitude results in around 8 times greater flow. In addition, the borehole flow rate decreases with the drainage time. Liu et al. [25] found similar trends.

The results presented in Figures 5 and 6 demonstrate that our model is reasonable and effective for the purpose of this modelling study, i.e., to evaluate the BRF method and its assumptions of excluding the gas desorption process and approximating using an ideal gas.

4. Estimation of Permeability from Model Output Using the BRF Method

To thoroughly evaluate the BRF method, a total of 126 cases were simulated, with two porosities, each porosity with seven permeabilities, each permeability with three gas desorption times, and each gas desorption time with three *in situ* gas contents, as listed in Table 2.

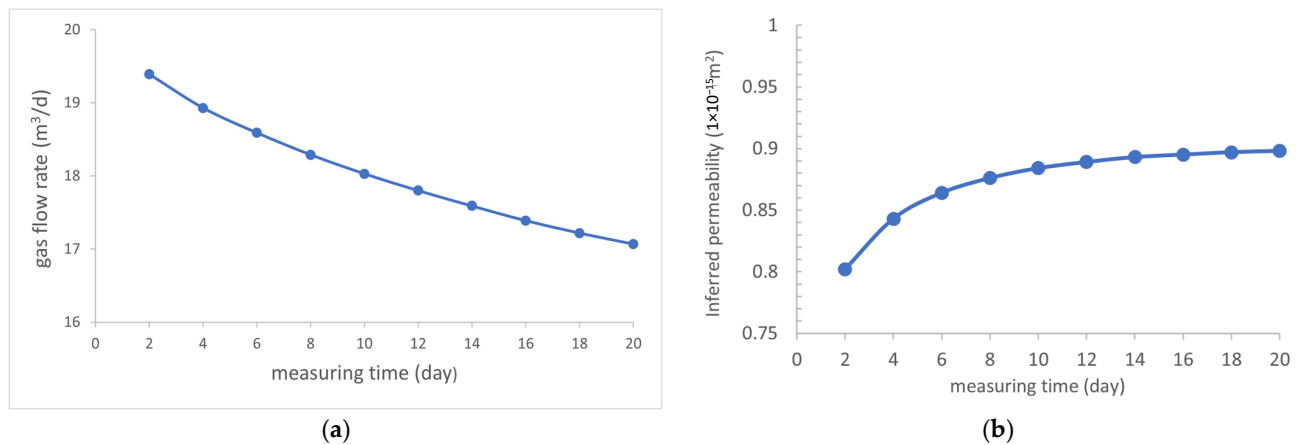
Using the outputs of the flow rates of the 126 numerical simulations, the permeabilities were calculated according to the BRF method, and the impacts of various parameters on the accuracy are presented in the following subsections.

4.1. Impact of Measurement Duration on the Accuracy

Table 3 shows the predicted permeabilities by the BRF method at different measuring times for the case with an input permeability of 10^{-15} m^2 , *in situ* gas content of $8 \text{ m}^3/\text{tonne}$, a porosity of 0.1, and a sorption time of 10 days. It contains measurements at 2, 4, 6, ..., 20 days. Figure 7 further plots the changes in the borehole flow rate and the estimated permeability with the measurement time. The estimated permeability values increase with the day of measurement, from $0.80 \times 10^{-15} \text{ m}^2$ on day 2 to $0.90 \times 10^{-15} \text{ m}^2$ on day 20. These values are 80% to 90% of the prescribed model permeability of 10^{-15} m^2 . Given that the experimental permeability measurements are always subject to considerable error, this accuracy is acceptable for the purpose of the gas drainage design and outburst control.

Table 3. Predicted permeabilities for different measuring times. The prescribed permeability for the case is 10^{-15} m^2 .

Measuring Time (day)	Flow Rate (m^3/d)	Predicted Permeability ($\times 10^{-15} \text{ m}^2$)
2	19.39	0.802
4	18.93	0.843
6	18.59	0.864
8	18.29	0.876
10	18.03	0.884
12	17.80	0.889
14	17.59	0.893
16	17.39	0.895
18	17.22	0.897
20	17.07	0.898

**Figure 7.** Time variation of (a) gas flow rate and (b) predicted permeability for the case of the input model permeability, 10^{-15} m^2 .

The trend of the estimated permeability with a measurement time indicates that the longer the measurement, the better the accuracy. However, after 10 days, the accuracy is not improved significantly; so, in the following analyses, the average permeability between 10 and 20 days is used to define the permeability of each study case.

4.2. Impact of Input Permeability on the Accuracy

The effect of permeability of the coal seam on the prediction accuracy of the BRF method is shown in Table 4, in which the *in situ* gas content is $8 \text{ m}^3/\text{tonne}$, and the desorption time constant is 10 days.

Table 4. Effect of input permeability on the accuracy (gas content = $8 \text{ m}^3/\text{t}$, $\tau = 10$ days, porosity = 0.10).

Model input permeability (m^2)	1.0×10^{-18}	1.0×10^{-17}	1.0×10^{-16}	1.0×10^{-15}	1.0×10^{-14}	1.0×10^{-13}
Predicted permeability (m^2)	0.99×10^{-18}	0.98×10^{-17}	0.91×10^{-16}	0.89×10^{-15}	0.88×10^{-14}	0.86×10^{-13}

With model input permeability varying between 10^{-13} m^2 and 10^{-18} m^2 , the BRF method predicts permeability with an accuracy of 86–100%. This suggests that the BRF method is applicable for coal seams within this permeability range.

The accuracy decreases with increasing input permeability. At the very low permeability of 10^{-18} m^2 , the accuracy is almost 100%. In contrast, the accuracy at the relatively high permeability of 10^{-13} m^2 is 86%. The declining accuracy with increasing permeability is likely to be related to the assumption of the BRF method that gas diffusion dominates Darcy

flow. Higher permeability of coal seam means higher Darcy flow rate or lower domination of the gas diffusion, and thus lead to reduced accuracy. This observation also agrees with findings by Liu et al. [25] who reported that coal matrix with large cleat spacing (this also means high permeability) cannot be adequately represented by a single porosity model as that assumed by the BRF method.

4.3. Impact of Gas Sorption Time on the Accuracy

Table 5 shows the predicted permeabilities for three sorption times. The predicted permeability is the same for the physically realistic sorption times (1 day and 10 days), suggesting that for real mining scenarios, sorption time will not impact the prediction accuracy. However, for the extreme case that has an unrealistically slow sorption time of 10^6 days, the accuracy is only 71%.

Table 5. Effect of sorption time on the accuracy (gas content = $8 \text{ m}^3/\text{t}$, porosity = 0.10).

Model Input Permeability (m^2)	Estimated Permeability (m^2) by the BRF Method		
	$\tau = 1 \text{ day}$	$\tau = 10 \text{ days}$	$\tau = 10^6 \text{ days}$
1.0×10^{-15}	0.89×10^{-15}	0.89×10^{-15}	0.71×10^{-15}

The sorption time constant (the time needed to adsorb 63.2% gas volume) reflects the gas diffusion rate. An extremely long sorption time (e.g., 10^6 days) leads to a distinguishably low diffusion rate and reduced domination of the gas diffusion over the Darcy flow. This departure from the assumption of the BRF method explains the low accuracy of the extreme case.

4.4. Impact of Gas Content on the Accuracy

The gas volume contained in the coal seam (gas content) is the most critical factor controlling the magnitude of an outburst if it occurs. Table 6 demonstrates that gas content has a limited impact on the prediction accuracy. The case with a low gas content of $4 \text{ m}^3/\text{t}$ is only 1% less in the prediction accuracy than the other two cases with high gas contents of $8 \text{ m}^3/\text{t}$ and $12 \text{ m}^3/\text{t}$.

Table 6. Effect of gas content (GC) on the accuracy (with $\tau = 10$ days and porosity = 0.10).

Model Input Permeability (m^2)	Estimated Permeability (m^2) by the BRF Method		
	GC = $4 \text{ m}^3/\text{t}$	GC = $8 \text{ m}^3/\text{t}$	GC = $12 \text{ m}^3/\text{t}$
1.0×10^{-15}	0.88×10^{-15}	0.89×10^{-15}	0.89×10^{-15}

A lower gas content results in a lower diffusion rate in the initial period of gas desorption; so, the gas diffusion is less dominant, meaning the BRF method estimation for the low gas content case is slightly less accurate. The gas content is also a reflection of the level of gas pressure in the coal seam through the relationship in Equation (16). Therefore, these results also show the impact of the initial gas pressure on the accuracy.

4.5. Impact of Porosity on the Accuracy

Table 7 compares the effect of coal porosity on the predicted permeability against various model input permeability values. The results indicate that the coal seam porosity has virtually no impact on the accuracy.

Table 7. Effect of porosity on the accuracy (gas content = $8 \text{ m}^3/\text{t}$ and $\tau = 10$ days).

Model input permeability (m^2)	1.0×10^{-18}	1.0×10^{-17}	1.0×10^{-16}	1.0×10^{-15}	1.0×10^{-14}	1.0×10^{-13}
Predicted permeability (m^2) at 0.05 porosity	0.99×10^{-18}	0.98×10^{-17}	0.91×10^{-16}	0.89×10^{-15}	0.88×10^{-14}	0.86×10^{-13}
Predicted permeability (m^2) at 0.10 porosity	0.99×10^{-18}	0.99×10^{-17}	0.91×10^{-16}	0.89×10^{-15}	0.88×10^{-14}	0.86×10^{-13}

5. Summary and Conclusions

Accurately estimating coal seam permeability is critical in coal seam gas extraction and gas outburst control. In Australia, coal seam permeability is normally inferred using the drill stem test or packer test, but Chinese coal mines estimate a parameter called the “gas conductivity coefficient” by measuring the borehole gas flow rate. It is, therefore, natural to wonder how closely the distinct Chinese method estimates coal seam permeability. Resolving this question will allow knowledge and experience in gas drainage and outburst management to be shared between Australian and Chinese coal mines.

Using a numerical modelling approach, this paper evaluates the accuracy of the Chinese method under various reservoir parameters. The model includes the gas desorption process, which is neglected in the assumptions of the Chinese method. The following conclusions can be drawn from the modelling results.

- (1) The borehole flow rate method predicts the permeability with an accuracy of approximately 85–100% under typical seam reservoir parameters. This accuracy would be adequate for a mine pre-drainage design and outburst control.
- (2) The actual permeability of the coal seam impacts the prediction accuracy more than any other parameters. The Chinese method is more accurate for lower permeability: it is almost 100% at a permeability of 10^{-18} m² (0.001 mD) but around 85% at a relatively high permeability of 10^{-13} m² (100 mD).
- (3) Other reservoir parameters, including the sorption time, porosity, and gas content/pressure have a negligible effect on the prediction accuracy.
- (4) The duration of the measurement could slightly affect the prediction accuracy. The longer the measurement, the higher the accuracy. However, for practical purposes, the accuracy is not improved significantly after 10 days of measurement.
- (5) The ease of the gas flow in the coal seam compared to the speed of the gas diffusion from the micropores to macropores controls the accuracy of the Chinese method. The reservoir parameters, which mean a low Darcy flow rate, such as a low permeability, or high diffusion rate, such as an extremely short sorption time, give high accuracy.

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