Interactions between coal seam gas drainage boreholes and the impact of such on borehole patterns

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Abstract

Borehole drainage is the most effective means of extracting coal seam gas. However, numerous boreholes are usually needed to create strong drainage from a single coal seam. When multiple boreholes work at the same time, borehole interactions will occur, which strongly affect the gas production and the area controlled by each borehole. To accurately quantify the degree of interaction, this paper utilizes the changes in the gas pressure at points around the borehole to calculate the pressure decrease coefficients, which reflect the degree of disturbance between the boreholes. The relationships between the physical parameters of the coal seam and the pressure decrease coefficients are studied with a typical double borehole interaction model. The results illustrate that the pressure decrease coefficients are positively correlated with the coal permeability in the disturbance region. Furthermore, the relation between the pressure decrease coefficients and borehole separation forms a negative exponential function, whereas the relation between the pressure decrease coefficients and the distance from the borehole forms a positive index function. Multi-borehole patterns are also

analyzed to investigate the ability of the pressure decrease coefficients to determine which common borehole pattern is most suitable for efficient gas extraction.

Keywords: Borehole interaction, Gas extraction, Borehole pattern, Numerical modeling

1. Introduction

Coal seam gas is a clean and efficient form of energy. However, this gas can cause disasters, such as coal and gas outbursts (An et al., 2013; Lunarzewski, 1998; Skoczylas et al., 2014) and gas explosions (Bao et al., 2016; Yang et al., 2014). Gas extraction remedies this issue and provides the opportunity to both furnish efficient energy and prevent gas disasters (Flores, 1998; Gilman and Beckie, 2000; Karacan et al., 2011). Gas extraction technology can generally be divided into two categories: borehole drainage and well extraction (Kong et al., 2014). Borehole drainage technology is the most widely used method in practical situations (Frank et al., 2013; Karacan et al., 2007; Zhai et al., 2016; Zheng et al., 2016).

Engineers are most concerned with the effects of borehole drainage. Thus, they often use the drainage radius of the borehole to assess the effect of extraction (Lin et al., 2016). Lee and Lam (2008) proposed that each borehole can be approximated by a square column that is circumscribed by the borehole radius. The methods of evaluating the borehole drainage radius can be divided into two categories: field measurements and theoretical analyses derived via numerical simulations. Field measurements are more accurate, but many boreholes must be drilled. Numerical simulations require considerably shorter processing and computational time, and although they may generate some errors, they provide values within acceptable ranges (Hao et al., 2012).

Both methods of drainage radius estimation tend to use a single borehole measurement.

However, gas extraction systems consist of multiple boreholes, and the interactions between the boreholes will significantly influence the drainage radius of each borehole in the system. Thus, for the results to accurately represent multi-borehole systems, the theory of multiple-boreholes in a coal seam must be studied. Studies of multi-lateral wells have been conducted and are relatively mature. The former Soviet Union was the first country to apply multi-lateral well technology to extract oil and gas. This technology was widely applied in Russia, the North Sea, and North America during the 20th century (Murillo et al., 2009). Eric Diggin's organization in the Shell Company held a forum on the technical progress on the use of multi-lateral wells and established the TAML (Technology Advancement of Multilaterals) ranking system (Fipke et al., 2008). Based on an incomplete set of statistics, approximately 1000 multi-lateral wells were drilled prior to 1998; by the end of the year, however, approximately 450 additional multi-lateral wells had been completed. By 2001, Baker Hughes and the Halliburton Company had developed more than 20 multi-lateral well systems independently, and approximately 2000 multi-lateral wells had been drilled around the world.

Current studies of multi-lateral wells focus on productivity prediction. The earliest method for productivity prediction was proposed by Табаков, who assumed that the pressure is equal at every point when there are 1 or 2 multi-lateral wells. However, with 3 or 4 multi-lateral wells, he assumed that the yield per unit length remains constant. This method clearly has several limitations, and the two assumptions are contradictory. S.D. Joshi proposed a new method that is based on Табаков's method but uses different assumptions; for example, the three-dimensional seepage problem was simplified as a vertical seepage and horizontal plane seepage problem, and the multi-lateral wells were assumed to be fractures with infinite

flow conductivity. His method can address the problems with Табаков's method and is more suitable for practical reservoir situations, so it is widely accepted (Joshi, 1988). Larsen (1996) developed a productivity prediction equation that incorporates quasi-steady-state flow. However, several assumptions are used in the equation for computing the productivity of multi-lateral wells; for example, all of the multi-lateral wells must be in a homogeneous reservoir with a constant thickness, and the distance between the midpoints of the multi-lateral wells is constant. These two assumptions restrict the application of the equation to a single reservoir; the first assumption is invalid when there is more than one reservoir, and second assumption is invalid when the multi-lateral wells are located in different reservoirs. Salas et al. (1996) divided fishbone multilateral wells into several small pieces and developed a one-way analytical model, but the interaction between wells was not considered. Turhan (2003) developed an unsteady, three-dimensional analytical model that was based on anisotropy and the skin effect. Chen et al. (2000) and Zhu et al. (2002) proposed a productivity prediction model that considered the cross-flow effect; however, it can only be used in the later quasi-stable period. Abdelhafid et al. (2003) applied the principle of potential superposition to develop a two branch well model and used it to calculate the infinite deflector solution.

The core of multi-lateral well research is the interaction phenomenon. Most of the aforementioned scholars considered the effect of interaction when they developed their productivity prediction models. Several investigators have conducted studies specifically on the interactions between wells. Zhang (1998) proposed that interactions between wells always occurred when two or more wells were used in the production of a single oil reservoir. He

believed that the pressure drop at any point should be equal to the sum of the pressure drop caused by each well at that point. Kong (1999) assumed that the area of the well groups was smaller than that of the reservoir and that each well was located far from the boundary of the reservoir. He utilized the pressure drop superposition principle to quantitatively represent the yield when one well is affected by other wells. Cases with different numbers of extraction wells and different patterns, both of which influence the interactions between the wells, were also discussed.

Inter-well interference is ubiquitous in the field of coalbed methane extraction and several researchers have studied this phenomenon in detail. Xu et al. (2013) developed an analytical model to predict the desorption area in coalbed methane (CBM) reservoirs and applied it to a CBM well group in the Hancheng field, China. He found that the desorption area expands with an elliptical geometry, and the final results predicted that well A and well B interfered with each other after 525 days of production. Xia et al. (2015) proposed a new convenient, efficient and reliable method to quantify well interference. The reliability of the method was verified by comparing the results with theoretical results for the real case of the Baode block. Well interference of coalbed methane wells is an effective technology to achieve high and stable gas production rates. Multi-branch horizontal coal bed wells have been used over the past 15 years to increase gas production rates considerably (Xian Baoan et al., 2005). A Z-pinnate well pattern that is drilled underbalanced in a low-permeability but high gas content coal seam can deplete 1200 acres from a single small well site and typically recover 85% to 90% of the original gas-in-place within 30 months (Wight, 2006). The performance of multi-branch horizontal wells was analyzed and compared to that of vertical wells (Ren et al.,

2014). Field data indicate that the gas production rate of most vertical wells decreased rapidly after a short period of time, while the performance of multi-branch horizontal wells was stable over 3 years of production.

Because the multi-borehole coal seam theory can be applied to research on multi-lateral wells and inter-well interference during coalbed methane extraction, we can also use the yield fluctuations of boreholes to express the degree of borehole interaction. However, this paper proposes a new quantitative parameter that can better describe the interactions between boreholes; the parameter is defined as the “pressure decrease coefficient” (PDC). The way in which the PDC can be represented and the relationship between the PDC and the physical parameters of coal are discussed. Finally, this paper proposes that the PDC can be used as a new criterion to evaluate which common drainage borehole layout pattern is best suited for coal seam gas extraction.

2. Description of the numerical model

2.1. Pressure decrease coefficients

When a coal seam is subjected to multi-borehole drainage, all of the boreholes contribute to the change of coal seam gas pressure. If one of the boreholes i is taken as the benchmark, and a point is regarded as the detection point, the linear distance between the point and borehole i is denoted by d . The gas pressure at this point is defined as $p_{id}(x, y, z)$. We note that the detection point is located on the line between the boreholes; $0 < d < \frac{1}{2}L$, where L represents the linear distance between the boreholes. If the interaction between the boreholes is ignored, the gas pressure at the detection point, $p_{id}(x, y, z)$, can be expressed as:

$$p_{id}(x, y, z) = p_{od}(x, y, z) - \sum_{j=1}^N p_j(x, y, z) \quad (1)$$

where $p_{od}(x, y, z)$ represents the gas pressure at the detection point when it is not disturbed by any boreholes, and $p_j(x, y, z)$ is the reduced gas pressure value at the detection point when it is affected by the boreholes, j . While the value of $p_j(x, y, z)$ is influenced by numerous factors, the relationship between them can be expressed as a function of f :

$$p_j(x, y, z) = f(k, ps, t, ds) \quad (2)$$

where k is the coal permeability, ps is the suction pressure of borehole j , t is the time of drainage, and ds is the linear distance between borehole j and the detection point. The coal permeability, the suction pressure of the borehole, and the extraction time are positively correlated with $p_j(x, y, z)$. In contrast, the linear distance ds is negatively correlated with $p_j(x, y, z)$.

The interaction between boreholes is considered when performing gas drainage. $T_{id}(x, y, z)$ denotes the gas pressure at the detection point. $p_{od}(x, y, z)$ represents the gas pressure at the detection point when it is not disturbed by any boreholes, and $p_{ij}(x, y, z)$ is the reduced gas pressure at the detection point when it is affected by the boreholes j . The boreholes j represent the boreholes other than borehole i . The gas pressure $T_{id}(x, y, z)$ can be defined as:

$$T_{id}(x, y, z) = p_{od}(x, y, z) - \sum_{j=1}^N p_{ij}(x, y, z) \quad (i = 1, 2, 3 \dots) \quad (3)$$

Because the value of $p_{ij}(x, y, z)$ includes the influence of the borehole i on the gas pressure at the detection point, Eq. (3) can be converted to:

$$T_{id}(x, y, z) = p_{od}(x, y, z) - p_{ii}(x, y, z) \left(1 + \sum_{j=1, j \neq i}^N \frac{p_{ij}(x, y, z)}{p_{ii}(x, y, z)} \right) \quad (i = 1, 2, 3 \dots) \quad (4)$$

In Eq. (4), the value of $p_{ii}(x, y, z)$ denotes the contribution of the reduced gas pressure

due to the borehole i . To simplify Eq. (4), we can define $\lambda_{ij} = \frac{p_{ij}(x, y, z)}{p_{ii}(x, y, z)}$ and omit the coordinate system, which is given as:

$$T_{id} = p_{od} - p_{ii} \left(1 + \sum_{j=1, i \neq j}^N \lambda_{ij} \right) \quad (i = 1, 2, 3 \dots) \quad (5)$$

Eq. (5) allows for the calculation of p_{od} and p_{ii} , which remain unchanged, and the value of λ_{ij} , which becomes larger with the increase of the reduced gas pressure p_{ij} . The variation leads to a decrease in the gas pressure at the detection point T_{id} .

In the studied coal seam, the initial gas pressure is considered to be equal everywhere and generally remains constant under the conditions of the numerical simulation. The parameter p_{od} represents the initial gas pressure at the detection point when it is not disturbed by any borehole, so the value of p_{od} is constant. Because the value of p_{ii} is completely determined by the conditions of the coal seam and the drainage time, it will remain constant for a given coal seam and drainage time. Thus, the assumption about the values of p_{od} and p_{ii} is reasonable, and the value of λ_{ij} can be regarded as an effective parameter that reflects the degree of interaction. In this paper, this parameter is defined as the pressure decrease coefficient (PDC): the greater the influence of borehole j on borehole i , the greater the value of the pressure decrease coefficient.

The PDC depends only on the physical properties of the coal and the locations of the boreholes and is not influenced by the rate of gas extraction.

2.2. Mathematical model of gas migration in coal seam

2.2.1. Governing equations for gas flow

Coal has the typical structure of a natural porous medium. It is widely accepted by researchers that coal consists of both coal matrix and fracture (Harpalani and Schraufnagel,

1990; Lu and Connell, 2007; Warren and Root, 1963). The gas in the coal matrix and the fracture are independent (Gray, 1987), as shown in Fig. 1.

Fig. 1 Illustration of coal, which is typically a dual-porosity system

In the coal seam, both free and adsorbing gas are controlled by a mass conservation equation (Chen et al., 2012; Danesh et al., 2016; Liu et al., 2010; Liu et al., 2015; Yao et al., 2016; Zhang et al., 2008):

$$\frac{\partial c}{\partial t} + \frac{\partial(\rho\phi)}{\partial t} = -\nabla m - \nabla(\rho V) \quad (6)$$

where C is the quantity of adsorbed gas per volume of coal matrix, kg/m^3 , ρ is the gas density, kg/m^3 , ϕ is the fracture porosity, %, m is the mass diffusion flux of the adsorbed gas, $\text{kg}/(\text{m}^3 \cdot \text{s})$, and V is the gas velocity of the free gas, m/s .

For the coal matrix system, the value of C can be calculated using the Langmuir equation (Crosdale et al., 1998; Langmuir, 1918):

$$c = \frac{pV_L}{p + P_L} \frac{M_c}{V_m} \rho_c \quad (7)$$

where V_L denotes the maximum adsorption capacity of coal, m^3/kg , P_L denotes the Langmuir pressure constant, pa , P is the gas pressure of coal, pa , V_m is the molar volume of methane under standard conditions, m^3/mol , ρ_c is the coal density, kg/m^3 , and M_c is the molar mass of methane, kg/mol .

m represents the mass diffusion flux of adsorbed gas. The gas diffusion in the coal matrix can be calculated using Fick's law (Liu et al., 2015; Wu et al., 2010):

$$m = -D\nabla c \quad (8)$$

where D is the gas diffusion coefficient, m^2/s .

For the coal fracture system, the relation between gas density and pressure is suit to the ideal gas law, ρ is given by the ideal gas law:

$$\rho = \frac{M_c}{RT} p \quad (9)$$

where M_c is the molar mass of methane, kg/mol, R is the universal gas constant, J/(mol • K), and T is the temperature of coal, K.

V is the gas velocity of free gas, and the gas flow in the coal fractures according to Darcy's law can be calculated as (Liu et al., 2015; Wu et al., 2010):

$$V = -\frac{k}{\mu} \nabla p \quad (10)$$

where V is the gas velocity in fracture, m/s, k is the fracture permeability, m², and μ is the methane viscosity, pa • s.

The combination of Eqs. (6)-(10) deduces the control equation of the gas flow field.

$$\frac{\rho_c V_T M_c p_T}{V_m (p + p_T)^2} \frac{\partial p}{\partial t} + \frac{M_c}{RT} \left[\phi \frac{\partial p}{\partial t} + p \frac{\partial \phi}{\partial t} \right] - \nabla (D \nabla c + \frac{\rho k}{\mu} \nabla p) = 0 \quad (11)$$

2.2.2. Boundary and initial conditions

Generally speaking, for the gas flow field, the boundary conditions can be defined as gas boundary and flux boundary. In a number of papers, these boundaries can also be called the Dirichlet and Neumann (Lu et al., 2016; Wu et al., 2010; Zhang et al., 2008). In this instance, they are defined as:

$$p = p(t) \text{ on } \partial\Omega \quad (12)$$

$$\frac{k}{u} \nabla p \bullet \vec{n} = Q(t) \text{ on } \partial\Omega \quad (13)$$

where $p(t)$ and $Q(t)$ are the known constant gas pressure and gas flux on the boundaries.

The initial conditions for coal seam can be expressed follows:

$$p = p_o \text{ in } \partial\Omega \quad (14)$$

3. Model validation

As shown in Section 2, the numerical model is composed of two parts: the pressure decrease coefficient (PDC) and a mathematical model of gas migration in the coal seam. The mathematical model of gas migration is used to control the gas flow, and the PDC is used to quantify the degree of borehole interaction. As shown in Eq. (4) and Eq. (5), the PDC is a simple algebraic expression that is only related to the coal seam gas pressure ($p_{ij}(x, y, z)$, $p_{ii}(x, y, z)$), and there is no coupling with the mathematical model of gas migration. To obtain the values of the PDC, the values of the coal seam gas pressure should be calculated first using the mathematical model of gas migration. Hence, if we want to demonstrate the accuracy of our numerical model, only need to illustrate that the mathematical model of gas migration is accurate.

We perform the following tests to validate the mathematical model of gas migration. The mathematical model is run to match the coal seam gas pressure data from Liu et al. (2015). They set up a model that consists of three horizontal layers, including a coal seam that measures 40 m across by 5 m tall is located between two rock layers. A methane drainage borehole with a radius of 0.1 m is located in the center of the coal seam, the initial gas pressure of the coal seam is 2 MPa, the suction pressure of the drainage borehole is 87 kPa and the initial coal permeability is $1 \times 10^{-16} \text{ m}^2$. No flow boundary conditions are applied to the coal seam. They then analyzed the gas pressure distribution in the coal seam under different numerical conditions. Only the case that considers the gas flow in the coal seam (without considering the permeability evolution due to compressive volumetric strain and matrix shrinkage, as well as the Klinkenberg effect) is relevant to this study. Hence, the gas

pressure data are collected under these conditions and compared with results of the mathematical model.

To better compare the gas pressure distribution of our mathematical model with the results from Liu et al. (2015), all of the conditions are consistent with those of Liu et al. (2015) except for the controlled model of gas migration. A pressure monitoring line ($y=2.5$, $x \in [20.2$ m, 40 m]) is established to monitor the change in the gas pressure of the coal seam at different drainage times. The gas pressure data of Liu et al. (2015) represent the pressure in the coal matrix blocks, which is different from the concept of gas pressure in our model. Only one gas pressure is considered in our model, which means that the gas pressure in the coal matrix blocks is always equal to that in the coal fracture. However, Liu et al. (2015) found that when the sorption time is 0.5 d, the gas pressure in the coal matrix blocks can be considered to be equal to that in the coal fracture, and the difference between them is difficult to distinguish. Hence, the gas pressure data can be compared with our simulated results. The comparative plots in Fig. 2 show that the gas pressure data are consistent with our simulation results at different gas drainage times (100 days, 250 days, 500 days), which demonstrates the accuracy of our model.

Fig. 2 Comparison between the results of our model and the data of Liu's model at different drainage times

4. Numerical simulation of multiple gas drainage holes in a single coal seam

Eq. (11) defines the equation for gas flow in the coal seam. This paper uses numerical simulation software to study the interactions between boreholes during coal seam gas extraction. The governing equation is controlled and expressed by the COMSOL Multiphysics finite element software, in which the “PDE module” is used to control the diffusion and

seepage flow of gas.

4.1. Geometric modes and condition state

To study the interactions between boreholes, the case of a single coal seam and two boreholes is discussed first. A numerical simulation model was constructed to study the pressure decrease coefficients that consider the interaction between gas drainage boreholes. To simplify the 3D model of the actual coal seam, the 2D geometric model is set as a rectangle that is 200 m long and 200 m wide. The simplified 2-D model will not affect the accuracy of the results and is conducive to analyzing the effect of gas redistribution and calculating the gas pressure during the extraction process (An et al., 2013; Perera et al., 2013; Wu et al., 2010; Ye et al., 2014). The 2-D model is also advantageous for the calculation, and its mesh allows easy convergence during computation. Reasonable model parameters and boundary conditions for flow were described in detail in Section 2.2.2. All of the boundaries are set to no flow conditions for the gas flow field as shown in Fig. 3.

Fig. 3 Geometry and boundary conditions of the coal seam

This paper considers the interactions between gas drainage boreholes when studying the PDC. The partial input parameters used in the coal seam model are listed in Table 1. However, because some of the input parameters are not measured in the field, we used values from recently published studies (An et al., 2013; Robertson, 2005; Zhang et al., 2008).

Table 1 Property parameters used in the numerical simulation of the coal seam

4.2. Results and analysis

This paper has discussed the methods and models that were used in this study and proposed that the PDC can describe the interactions between boreholes. In the following section, we will discuss the ways in which the COMSOL Multiphysics finite element software

is used to understand what factors influence the PDC and how these factors affect the value.

4.2.1. Relation of *the* PDC to coal permeability

To research the numerical relationship between *the* PDC and coal permeability in *the* double borehole mode, *a* single borehole mode and *a* double borehole mode are established. We utilize the geometric model described above to construct *the* different modes and set the parameters for different modes. In *the* single borehole mode, the coordinates of drainage borehole A are (90 m, 100 m). In *the* double borehole mode, the coordinates of the two drainage boreholes are A (90 m, 100 m) and B (110 m, 100 m); the distance between the two boreholes is 20 m. Whether in the single or the double borehole mode, the radius of all *the* boreholes is 0.1 m, the suction pressure is 0.0085 MPa, and the gas drainage time is 100 days. We used coal seams with different permeability to simulate the drainage process with *the* different borehole modes and calculated the gas pressure at the detection point C (94 m, 100 m) at *a* drainage time of 100 days. The values of *the* gas pressure and the PDC are shown in Fig. 4.

Fig. 4 Values of the PDC and gas pressure at the detection point in the different modes

The numerical analysis of the gas pressure at the detection point C under *the* different borehole modes shows that when the coal permeability is less than $2 \times 10^{-18} \text{ m}^2$, the gas pressure is nearly the same in *the* different borehole modes. Small fluctuations appear only when the coal permeability is approximately $2 \times 10^{-18} \text{ m}^2$. The gas pressure remains consistent under *the* different borehole modes when the coal permeability is less than $1 \times 10^{-18} \text{ m}^2$. Hence, the values of the PDC are 0 or close to 0 when the coal permeability is less than $2 \times 10^{-18} \text{ m}^2$, which illustrates that interactions between boreholes do not occur under these permeability conditions. As shown in Fig. 4, the entire region is divided into two

parts: a non-disturbance region and a disturbance region. In the disturbance region, the PDC increased gradually with increasing coal permeability; this phenomenon reflects the notion that the greater the coal permeability, the stronger the interactions between boreholes. However, the PDC remains constant when the coal permeability increases beyond a specific value. This trend indicates that the degree of interaction between boreholes will not increase after the coal permeability exceeds this value.

These conclusions are based on boreholes that are located 20 m apart and a fixed detection point. If these assumptions change, the value of the coal permeability that is used to divide the non-disturbance region and disturbance region, will change, as will the values of the PDC. However, the general trends are the same.

4.2.2. Relation of the PDC to the borehole separation

To quantify the relationship of the PDC to the borehole separation, a single borehole and a double borehole mode are established. For the single borehole mode, the coordinates of the drainage borehole A are (60 m, 100 m). In the double borehole mode, the distance between the two boreholes should be varied to study the relation of PDC to borehole separation; thus, the coordinates of borehole A are fixed, while the coordinates of borehole B are varied. Whether for the single borehole mode or the double borehole mode, the radius of all the boreholes is 0.1 m, the suction pressure is 0.0085 MPa, the gas drainage time is 100 days, and the coal permeability is $1 \times 10^{-16} \text{ m}^2$. Using different borehole separations to simulate the drainage process, we extracted the values of the gas pressure at detection point C (64 m, 100 m) at a drainage time of 100 days. The values of the gas pressure and the PDC are shown in Fig. 5.

Fig. 5 Values of the PDC and gas pressure at the detection point with increasing borehole

separation

As shown in Fig. 5, the PDC decreases with increasing borehole separation. By fitting the data, the curve can be approximated by the decreasing exponential function $\lambda = e^{-0.05013L}$, and the degree of curve fitting is approximately 96.8%. Fig. 5 shows that the values of the PDC initially decrease rapidly with increasing borehole separation and that the PDC approaches zero when the borehole separation increases to a certain value, which illustrates that the interactions between boreholes may be ignored if the borehole separation is sufficiently large.

These conclusions are based on a coal permeability of $1 \times 10^{-16} \text{ m}^2$ and a fixed detection point. If the coal permeability or the location of the detection point change, the relationship between the PDC and the borehole separation would also change, as would the values of the PDC. The variation of the PDC can be denoted by a decreasing exponential function, which is illustrated in Eq. (15). The value of A will vary with different conditions, and L represents the borehole separation:

$$\lambda = e^{-AL} \quad (15)$$

4.2.3. Relation of the PDC to distance from the borehole

A value of the PDC can only reflect the interaction at one point around the studied borehole. If we want to understand the interaction across the entire drainage area, the relationship between the PDC and distance from the borehole must be understood. To quantify this relation, single borehole and double borehole mode are established. In the single borehole mode, the coordinates of drainage borehole A are (60 m, 100 m). In the double borehole mode, the coordinates of the drainage boreholes are A (60 m, 100 m) and B (140 m, 100 m) and the borehole separation is 80 m. In both the single and double borehole mode, the

radius of all the boreholes is 0.1 m, the suction pressure is 0.0085 MPa, the gas drainage time is 100 days, and the coal permeability is $1 \times 10^{-16} \text{ m}^2$. Because there are numerous points within the area of influence, to accurately reflect the relationship between the PDC and the distance from the borehole, the values were extracted along the line connecting the two boreholes, which are shown in Fig. 6.

Fig. 6 Values of the PDC along the line connecting the two boreholes

In this paper, the meaning of λ_{BA} and λ_{AB} are different; λ_{BA} represents a situation in which borehole A interferes with borehole B, whereas λ_{AB} represents the case in which borehole B interferes with borehole A. As shown in Fig. 6, the two curves are completely consistent and symmetrical due to the symmetrical locations of boreholes A and B. If the boreholes are not symmetrical, the curves of the PDC will not be consistent and symmetrical. The value of the PDC increases with increasing distance from the borehole, and the curve is approximated by a positive exponential function. The rate of increase of the curve is small initially but increases significantly when the distance from the borehole is increased further.

These conclusions are for a coal permeability of $1 \times 10^{-16} \text{ m}^2$ and a fixed borehole separation. If the coal permeability or the borehole separation is changed, the relationship between the PDC and the distance from borehole will also change, but the curve will still be represented by a positive exponential function.

4.3. Situation of multiple drainage boreholes

Natural coal seam gas drainage systems are complex. One of the biggest differences compared to the simulation is the number of boreholes; the number of boreholes is much larger in reality than in simulations (Spencer et al., 1987; Wei et al., 2016; Ye et al., 2014). The previous analyses used a double borehole mode to analyze the interactions between

boreholes during gas drainage. However, in a drainage system, each borehole is affected by all of the other drainage boreholes; interactions occur between each pair of boreholes. A typical gas drainage system is shown in Fig. 7(a).

Fig. 7 Realistic coal seam gas drainage system

The degree of borehole interaction is studied using the simplest double drainage borehole mode in the numerical simulation, which utilizes the quantitative parameter of the PDC. Several correlations have been drawn based on the relationship between the PDC and several factors. These correlations are also applied in the new multiple borehole mode. Because the basic mechanism of borehole interaction is the same, the only difference is the number of boreholes. When one borehole is disturbed by several boreholes at once, the other boreholes can be assumed as an integrated whole that is equivalent to one borehole through the mathematical abstraction method, which is shown in Fig. 7(b). This hypothetical whole only differs from an actual single borehole in its basic physical properties, such as its location and radius. Hence, the correlations of the interactions between multiple-boreholes are consistent with those of the double borehole mode. However, there are several specific differences; the multi-borehole mode will alter the slopes of these graphs, but not their form. To demonstrate this conclusion, the presence of nine drainage boreholes in a single coal seam is simulated. Several curves of the PDC under different conditions are shown in Fig. 8.

Fig. 8 Relationships between several factors and the PDC for the case of nine boreholes

5. Discussion on the borehole pattern

The layout pattern of drainage boreholes directly influences the effect of coal seam gas extraction. Two factors determine the borehole pattern: the distance between the boreholes and the arrangement mode of the boreholes. The distance between the boreholes clearly

influences the coal seam gas extraction; the more intensive the drilling, the better the gas extraction. In reality, for a fixed coal seam volume, the smaller the distance between the boreholes, the greater the number of boreholes. An increase in the number of boreholes will lead to an increase in cost, so decreasing the distance between the boreholes to increase gas extraction is not a reasonable option for the coalmine enterprise (Dong et al., 2015). Thus, choosing an appropriate arrangement mode of boreholes becomes vital for gas drainage. Several typical arrangements of boreholes are shown in Fig. 9.

Fig. 9 Typical arrangement modes of boreholes in the field

The value of the PDC quantitatively reflects the degree of interaction between boreholes; the greater the PDC, the more significant the interactions. The results presented above indicate that the interactions between boreholes can improve the gas extraction; the greater the interactions, the better the gas extraction. Hence, we can use the value of the PDC to reflect the effect on gas extraction.

There are three typical layout patterns of drainage boreholes. In both the rectangle mode and the rhomb mode, the distance between the boreholes is 15 m. In the trapezoid mode, the average distance between the boreholes on the upper and lower sides is 15 m. As usual, the radius of the boreholes is 0.1 m, the suction pressure is 0.0085 MPa, the gas drainage time is 100 days, and the coal permeability is $1 \times 10^{-16} \text{ m}^2$. To facilitate an analysis of which mode is best for coal gas extraction, the same number of boreholes is used to form the basic geometric models in the different modes. Values of the PDC at a location 4 m above the center borehole in the basic geometric model are obtained for a gas drainage time of 100 days. The values of the PDC and the quantities of extracted gas for the different layout patterns are shown in Fig.

10 and Fig. 11.

Fig. 10 Values of the PDC for different layout patterns of boreholes

Fig. 11 Quantities of extracted gas for different layout patterns of boreholes

The values of the PDC for the same coal seam and location differ for the different layout patterns. As shown in Fig. 10, the maximum value of the PDC is 1.4933, which corresponds to the rhombus mode. If this PDC value is used as a judgment index, the layout pattern of rhombus is better than both the rectangle and trapezoid modes. This conclusion is consistent if the quantity of extracted gas is used as the parameter to determine the best patterns. The maximum quantity of extracted gas is 7875.4585 m^3 , which also corresponds to the rhombus mode. This analysis demonstrates that using the PDC as a judgment index is valid.

6. Conclusions

Interactions between boreholes are ubiquitous during coal seam gas drainage. To accurately quantify the degree of interaction, the parameter of the PDC is proposed. This parameter is based on the change in gas pressure. Several numerical simulation models were constructed to study the relationship between different factors and the PDC. Based on these calculations, we propose that the PDC can also be used as an index to determine which layout pattern of boreholes is better for coal seam gas extraction. The major findings are summarized as follows:

(1) The double borehole mode is used to better understand the interaction between two boreholes. The results show that the values of the PDC increase gradually with increasing coal permeability, but if the coal permeability is too low, the interactions between boreholes can be ignored. The relationship between the PDC and the distance between the boreholes is approximated by a decreasing exponential function with increasing distance. The PDC always

increases with **increasing** distance from the borehole, and the curve is represented by a positive exponential function.

(2) The correlations **from the** double borehole mode **were** applied to the multi-borehole mode. Because the basic mechanism of the borehole interaction **is the same**; the only difference is the number of boreholes. The boreholes can be divided into two groups using the method of mathematical abstraction. Each group contains many boreholes, which are made **equivalent to a single** borehole. **Thus**, the multi-borehole mode can be equivalent to the double borehole mode. However, **there are several specific differences**; the multi-borehole mode will **change** the slopes of these graphs but not their form.

(3) The value of the PDC **reflects** the degree of interaction between boreholes; the greater the interaction, the better the effect on gas extraction. **The values of the PDC were calculated for** common borehole layout patterns, and the results indicated that the rhombic pattern **provides better** gas extraction than the rectangular and trapezoid patterns.

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Figures

Fig. 1 Illustration of coal, which is typically a dual-porosity system

Fig. 2 Comparison between the results of our model and the data of Liu's model at different drainage times

Fig. 3 Geometry and boundary conditions of the coal seam

Fig. 4 Values of the PDC and gas pressure at the detection point in the different modes

Fig. 5 Values of the PDC and gas pressure at the detection point with increasing borehole separation

Fig. 6 Values of the PDC along the line connecting the two boreholes

Fig. 7 Realistic coal seam gas drainage system

Fig. 8 Relationships between several factors and the PDC for the case of nine boreholes

Fig. 9 Typical arrangement modes of boreholes in the field

Fig. 10 Values of the PDC for different layout patterns of boreholes

Fig. 11 Quantities of extracted gas for different layout patterns of boreholes

Table

Table 1 Property parameters used in the numerical simulation of the coal seam

Parameter	Value
Temperature, T	293 K
Density of coal, ρ_c	1250 kg/m ³
Langmuir volume constant, V_L	0.0228 m ³ /kg
Langmuir pressure constant, P_L	1.41 MPa
Initial pressure of coal	4.0 MPa
Initial porosity of fractures, Φ	0.072
Diffusion coefficient, D	3.6*10 ⁻¹² m ² /s
Molar mass of methane, M_c	0.016 kg/mol
Gas constant, R	8.4135 J/mol/K
Gas viscosity coefficient	1.08e-5 Pa*s
Molar mass of coal gas	22.4 L/mol