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Investigation on the Gas Drainage Effectiveness from Coal Seams by Parallel Boreholes

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Abstract: Gas drainage is an important technology to prevent coal and gas outburst, and the drained gas is a kind of clean energy. The gas pressure can characterize gas drainage effectiveness. In this paper, we investigated the effectiveness of gas drainage by gas pressure. Determined by the space shape of the gas flow field, the gas flow state surrounding the drainage boreholes is radial flow. According to the basic equations of radial flow, discrete equations were achieved by the implicit difference scheme, and then we obtained the gas pressure surrounding the drainage boreholes. Results showed that the midpoint between two holes presents the highest gas pressure, and gas pressure declined from the midpoint of two boreholes to both sides. The midpoint gas pressure of the two holes reflects gas drainage effectiveness in a certain degree. Gas pressure declined with segmented characteristics in the first period decline curve in the form of a cubic curve, and the second period decline curve in the form of a straight line. When the drainage pressure reaches a certain value, the decline rate of gas pressure had little relationship with the drainage negative pressure, mainly influenced by the permeability coefficient. To improve the drainage effectiveness, anti-reflection measures are feasible, instead of increasing the drainage negative pressure. Moreover, the conclusion was verified by field data.

Keywords: radial flow; implicit difference scheme; decline rate; segmented characteristics; negative pressure; permeability coefficient

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1. Introduction

The rapid and sustainable development of China's economy has increased the demand for coal. Many coal mines have started deep mining to depths of 800–1500 m. The increase in mining depth has resulted in increased geostress, increased gas pressure, and increased gas content. Consequently, coal and gas outburst, gas explosions, and other disasters have become increasingly serious. Gas drainage is an important measure to prevent coal and gas outburst, and the drained gas is a kind of clean energy. Therefore, gas drainage is of great significance for mining safety and clean energy. The effectiveness of gas drainage must be considered in the design of gas drainage, and gas pressure is an important index to measure the effectiveness of gas drainage [1–3]. The allowed gas pressure of a gas outburst seam is less than 0.74 MPa after taking the outburst prevention measures. Many scholars carried out gas drainage simulation studies, but they focused on the simulation of single drainage hole. In practice, there are a lot of gas drainage holes working simultaneously in the gas drainage [4–7].

In this paper, the effectiveness of gas drainage was evaluated by the gas pressure in the midpoint of the two holes. According to the basic equations of radial flow, and the implicit difference scheme, we obtained the gas pressure by MATLAB programming. This study is of great significance to gas drainage design.

2. Methods

2.1. Basic Radial Flow Equations of the Gas Surrounding the Drainage Borehole

Assumption conditions:

(1) The change of the gas pressure has little influence of the permeability and porosity of the coal seam;
(2) The temperature changes little in the gas flow field, and the gas flow in the coal seam is isothermal;
(3) Gas is the ideal gas, and the gas flow in the coal seam follow Darcy law.

Determined by the space shape of the gas flow field, the gas flow state surrounding the drainage boreholes is radial flow. The gas radial flow follows the following three equations [8].

(1) Approximate equation for gas content,

$$X = \alpha\sqrt{p} \tag{1}$$

where X represents the gas content of coal seam, m^3/t; α is the seam gas content coefficient, $m^3/(t{\cdot}MPa^{1/2})$; p is the gas pressure, MPa;

(2) Law of conservation of mass,

$$\frac{\partial X}{\partial t}\left[\pi(r+dr) - \pi r^2\right]m + \frac{\partial Q}{\partial r}dr = 0 \tag{2}$$

where r is radius, m; m is coal seam thickness, m; Q is gas emission from drainage, m^3/d;

(3) Darcy Law,

$$q = -\lambda\frac{dP}{dn} \tag{3}$$

where q is the gas flow through one square meter at the atmospheric pressure and a certain temperature, $m^3/(m^2{\cdot}d)$; λ is permeability coefficient of coal seam, $m^2/(MPa^2{\cdot}d)$ P is the gas pressure p squared, MPa^2.

The equation of gas radial flow can be written as

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} = \frac{\alpha}{4\lambda}P^{\frac{3}{4}}\frac{\partial P}{\partial t} \tag{4}$$

For easy of calculation, the equation was simplified by approximate substitutions, that $P^{\frac{3}{4}} = P_0{}^{\frac{3}{4}}$.

$$\frac{\partial P}{\partial t} = a_1\left(\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r}\right) \tag{5}$$

where $a_1 = \frac{4\lambda}{\alpha}P_0{}^{-\frac{3}{4}}$.

The boundary conditions are that $r = 0, P = P_1$, where P_0 represents the square of the seam original gas pressure.

2.2. Numerical Simulation of Radial Flow

It is difficult to get the analytical solution of gas radial flow equations. This paper calculated the equations by the finite difference method in the implicit scheme [9–13]. The equation solution obtained by implicit difference scheme is unconditional stability, and the time step and space interval can be selected independently. Take the space between boreholes 3 m and drainage time 120 d as the case to calculate. Boreholes are arranged as Figure 1.

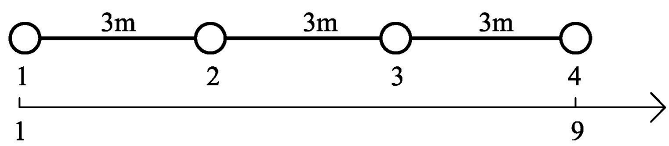


Figure 1. Boreholes arrangement.

The drainage parameters are shown as Table 1.

Table 1. The drainage parameters [14].

Permeability Coefficient $m^2/(MPa^2 \cdot d)$	Gas Content Coefficient $m^3/(t \cdot MPa^{1/2})$	Original Gas Pressure /(kPa)	Negative Drainage Pressure /(kPa)	Time Step /(d)	Space Interval /(m)
135	10.25	560	−50	1	0.1

Only the pressure of the points locating on the connecting-lines of borehole centers has been considered. The pressure was simplified by one-dimension and calculated by MATLAB programming. Considering the gas pressure changes over time, the partition table are shown as Table 2. The horizontal axis is time and the vertical axis is distance.

Table 2. Partition table.

1	61	...	....	....	10,981
2	62	.....	(i − 1, j)	.....	.....
3	63	(i, j − 1)	(i, j)	(i, j + 1)	....
....	.....	......	(i + 1, j)	......	....
91	182	.....	.....	.....	11,011

First derivative of gas pressure on time by backward difference [15]:

$$\frac{\partial P}{\partial t} = \frac{P(i,j) - P(i,j-1)}{\Delta t} \tag{6}$$

First derivative of gas pressure on radius by backward difference:

$$\frac{\partial P}{\partial r} = \frac{P(i,j) - P(i-1,j)}{\Delta r} \tag{7}$$

Second derivative of gas pressure on radius by central difference:

$$\frac{\partial^2 P}{\partial r^2} = \frac{P(i+1,j) - 2P(i,j) + P(i-1,j)}{(\Delta r)^2} \tag{8}$$

We obtained the discrete equation when combining Formulas (6)–(8) and Formula (5).

$$P(i,j) - P(i,j-1) = \frac{a_1}{i(\Delta r)^2}[iP(i+1,j)(1-2i)P(i,j) + (i-1)P(i-1,j)] \tag{9}$$

The boundary conditions are as follows: boreholes in the points of 0 m, 3 m, and 9 m, and the negative drainage pressure is −50 kpa.

$$P(31,:) = 2500;\ P(61,:) = 2500;\ P(91,:) = 2500$$

The initial conditions are that

$$P(1,2:30) = 313,600;\ P(1,32:60) = 313,600;\ P(1,32:60) = 313,600.$$

Coefficient matrix P of equations was obtained by Formula (6).

When i = 2:90, or i = 1:91:10,921, or i = 31:91:10,951, or i = 61:91:10,981, or i = 91:91:11,011, P(i, i) = 1;

j = 2:121.

When i = 91 × (j − 1) + 2:91 × j − 61 or i = 91 × (j − 1) + 32:91 × j − 31 or i = 91 × (j − 1) + 62:91 × j – 1 (rem is Mod of remainder),

P(i, i − 91) = 1;

P(i, i − 1) = 0.4/rem(i, 91) × (rem(i, 91) − 1;

P(i, i) = −1 − 0.4/rem(i, 91) ×(2*rem(i, 91) − 1);

P(i, i + 1) = 0.4.

We obtained the B based on the boundary conditions and initial conditions.

When i = 2:30 or i = 32:60 or i = 62:90,

B(i, 1) = 313,600.

When i = 1:91:10921, or i = 31:91:10,951, or i = 61:91:10,981, or i = 91:91:11,011,

B(i, 1) = 2500.

We obtained the dynamic gas pressure of the points at a difference distance form borehole. The result of the calculation is shown in Figure 2.

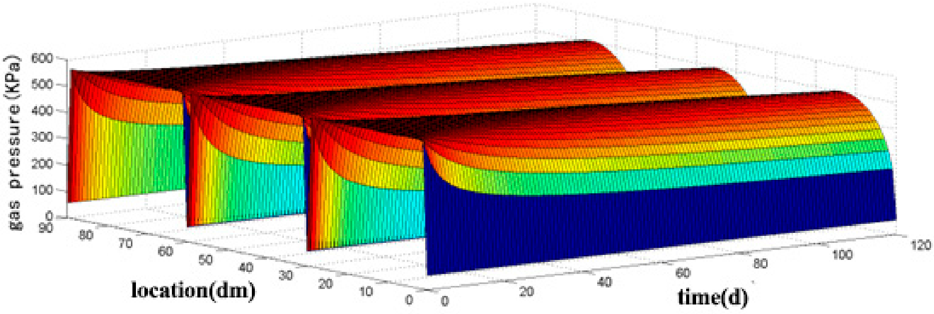


Figure 2. The result of calculate.

3. Results and Discussion

3.1. The Decline Law of Midpoint Gas Pressure between Two Holes

Results showed that the midpoint between the two holes presents the highest gas pressure, and gas pressure declined from the midpoint of two drilling holes to both sides, which can be observed from Figure 3. The gas pressure in the midpoint of two holes is larger than that in both sides. To demonstrate this feature more clearly, the gas pressure in different points after 120 days of gas drainage was shown in Figure 3. We analyzed gas pressure in the midpoint between two holes to evaluate the effectiveness of gas drainage.

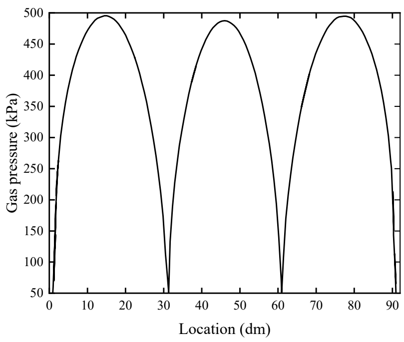


Figure 3. The gas pressure after drainage 120 days later.

The decline curve of gas pressure in the point of 1.5 m is shown in Figure 4. From the curve, we can find that the decline curve is in the form of cubic curve in the first 60 days, and in the form of straight line in the second 60 days.

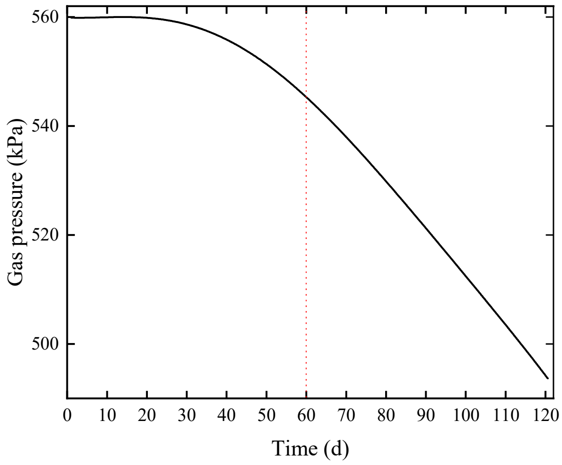


Figure 4. The decline law of 1.5 m gas pressure.

The decline curves in the first 60 days and the second 60 days were fitted (as shown in Figures 5 and 6). The result showed that the correlation coefficient of the first 60 days decline curve in the form of cubic curve reached 0.9993 and the correlation coefficient of the second 60 days decline curve in the form of straight line reached 0.9991, which certified that gas pressure declined in segments. Gas pressure declined with segmented characteristics; the straight curve of the second 60 days, especially, has certain significance in forecasting the gas drainage effectiveness.

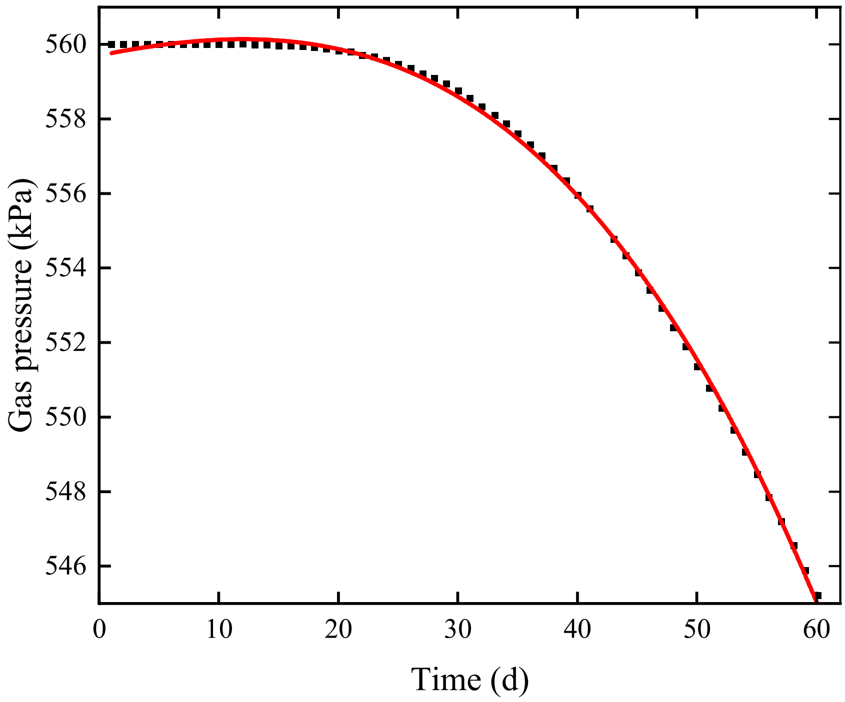


Figure 5. The fitting curve of first 60 days gas pressure.

The fitting result of first 60 days:
$y = -0.00006027x^3 - 0.001505x^2 + 0.06212x + 559.7; R^2 = 0.9993.$
The fitting result of second 60 days:
$y = -0.8637x + 598.5; R^2 = 0.9991.$

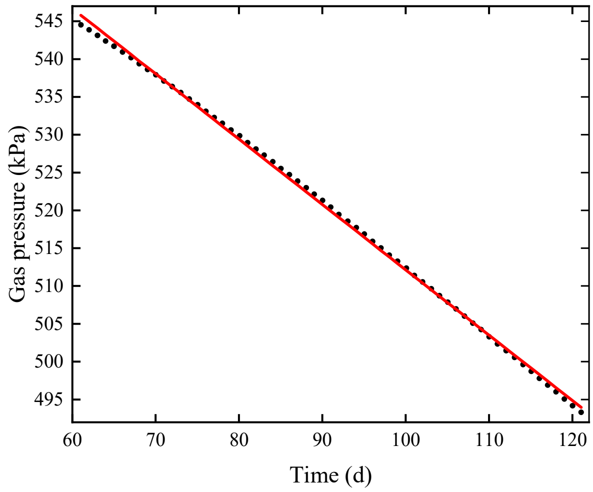


Figure 6. The fitting curve of second 60 days gas pressure.

3.2. The Relationship between Gas Pressure and Negative Drainage Pressure and Permeability Coefficient

Negative drainage pressure and permeability coefficient are the important factors in the design of gas drainage; thus, we investigate the relationship between gas pressure and negative drainage pressure and permeability coefficient.

The decline curves of gas pressure in the second 60 days under different negative drainage pressures are shown in Figure 7.

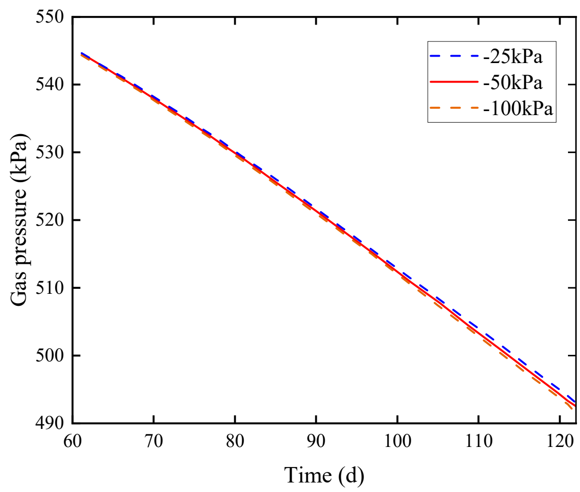


Figure 7. The decline curves of gas pressure in the second 60 days under different negative drainage pressures.

From Figure 7, we can conclude that the negative drainage pressure has little influence on gas pressure decline rate, but a bigger drainage negative pressure will lead to more air leakage and more power of the pump. As a result, it is unreasonable to improve the gas drainage effectiveness by improving negative drainage pressure.

The decline curves of gas pressure in the second 60 days under different permeability coefficients are shown in Figure 8.

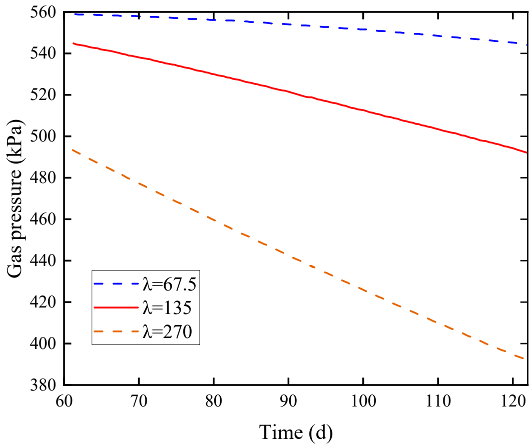


Figure 8. The decline curves of gas pressure in the second 60 days under different permeability coefficients.

From the intercepts of the gas pressure decline curves in Figure 8, we can conclude that the permeability coefficient has a great influence on the gas pressure declining quantity in the first 60 days. From the slopes of the gas pressure decline curves in Figure 8, we can also conclude that the permeability coefficient has a great influence on the gas pressure decline rate in the second 60 days. As a result, the enhancement of the permeability coefficient can improve the gas drainage effectiveness well.

3.3. Validation of Segmented Pressure Decline

The fourth coal seam of the Tingnan coal mine is locatsed in the Jurassic middle Yanan group [16]. The coal in fourth coal seam is low metamorphic bituminous coal with low ash, special low sulfur, low phosphorus, and medium and high heat. Macroscopic types of coal mainly consist of semibright coal and semidull coal. The apparent density of coal changes among 1.24~1.59 t/m^3. In the west mine second panel, the 204 working face is located. The gas pressure is 0.6 MPa, the gas content is 5.72~6.64 m^3/t, the adsorption constant a is 21.466~24.719 m^3/t, and b is 0.725~0.941 MPa^{-1}. The coal seam average angle is 3 degrees, the average thickness is 19.1 m, the mining thickness is 6 m, the permeability coefficient of coal seam is 2.5935 $m^2/(MPa^2{\cdot}d)$, the attenuation coefficient of gas flow of borehole is 0.0138~0.0178 d^{-1}, and the seam belongs to drainable coal seam. According to the actual production situation of The Tingnan coal mine, we chose the 204 working face to measure the gas pressure. The pressure hole is located in the middle of two drainage boreholes, which are 6 m apart. The borehole parameters are listed in Table 3.

Table 3. Borehole parameters.

Borehole	Borehole Diameter/(mm)	Borehole Depth/(m)	Angle/(°)	the Distance to Floor /(m)	Sealing Materials	Sealing Depth/(m)
Pressure borehole	75	50	1~2	1.2	cement mortar	20
Drainage borehole	94	60	1~2	1.2	polyurethane	5

The gas pressure in pressure hole after the drainage is shown in Figure 9.

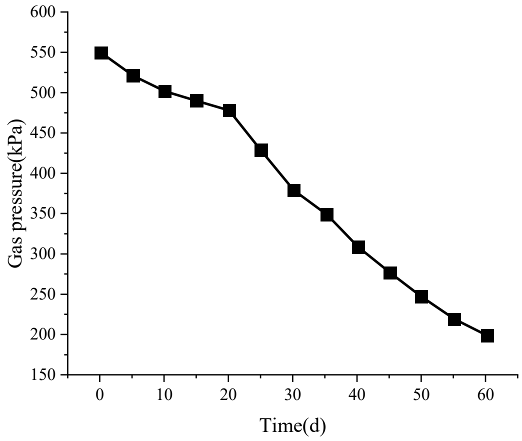


Figure 9. The curve of gas pressure.

The fitting curve of gas pressure in first 30 days is shown in Figure 10.

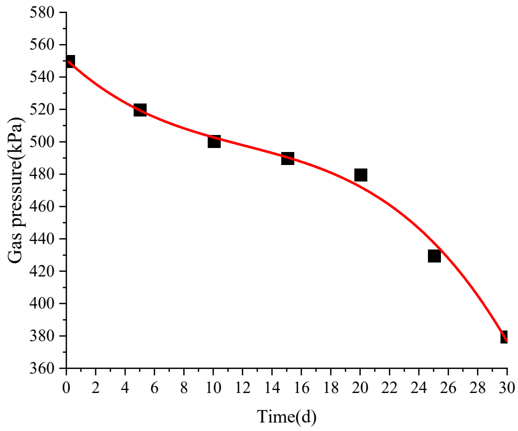


Figure 10. The fitting curve of gas pressure in first 30 days.

$y = -1E - 05x^3 - 0.008x + 0.549;\ R^2 = 0.892.$

The fitting curve of gas pressure in second 30 days is shown in Figure 11.

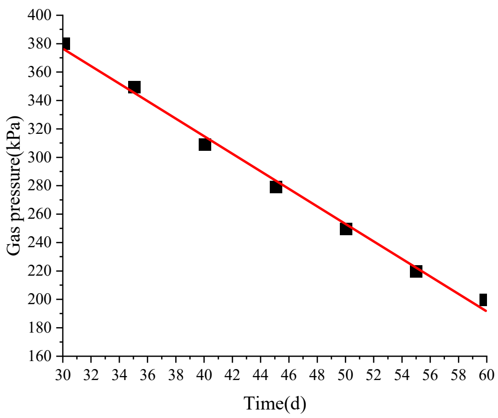


Figure 11. The fitting curve of gas pressure in second 30 days.

$y = -0.006x + 0.560;\ R^2 = 0.894.$

From the curve in Figures 10 and 11, we find that the decline curve is in the form of cubic curve in the first 30 days, and the form of straight line in the second 30 days, which verifies the conclusion in this paper that gas pressure decline presents segmental characteristics. The main finding of this study is that there are segmental characteristics of gas pressure decline in gas drainage. As for the duration of the two periods, it is related to the gas occurrence and drainage parameters.

3.4. The Verification of the Influnces of Negative Drainage Pressure on the Gas Pressure Decline Rate

The experiment of gas drainage was conducted in the Li Feng coal mine [17]. The negative drainage pressure only influences the area around the borehole 3–5 m, and when the negative drainage pressure reaches 27 kpa, it has less influence on gas drainage volume and has little influence on the aera far from borehole 6 m, which can be seen from Figure 12. As a result, it is not reasonable to add the gas drainage volume by improving the negative drainage pressure without an enhancement of the permeability coefficient.

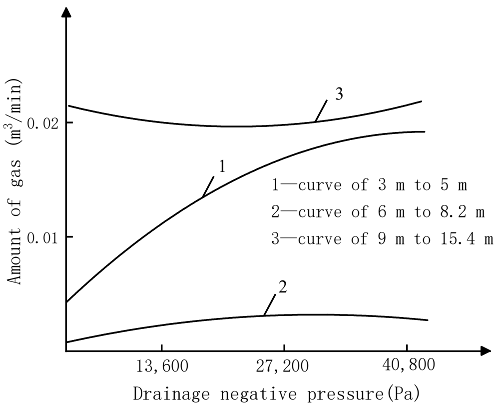


Figure 12. The relationship between negative drainage pressure and gas drainage volume.

The field experiment indicates that improving negative drainage pressure has little effect on the gas drainage volume, which validates the previous calculation results. If we want to improve the gas drainage volume in the design of gas drainage, there is little effect by improving the negative drainage pressure. Moreover, the pump power will increase and the air leakage will deteriorate. As a result, it is not reasonable to improve the gas drainage volume by improving the negative drainage pressure.

3.5. The Verification of the Influence of Permeability Coefficient on the Gas Pressure Decline Rate

In the Tan Jia Chong coal mine, the 2264-1N-S working face is located in the No.6 coal seam, and the average thickness of coal seam is 8.4 m. The working face is located in the thick coal seam and gas emission quantity is relatively large [18]. The absolute gas emission rate of the 2264-1N-S coal mining face in the Tan Jia Chong coal mine is more than 20 m^3/min. The gas drainage effectiveness of the present measure is poor, which leads the tail-gate gas concentration overrun frequently. Therefore, the coal seam hydraulic fracturing technology was applied to improve the gas drainage effectiveness. The hydraulic fracturing experiment was conducted in the 2264-1N-S working face tail-gate. Hydraulic fracturing holes were arranged between the drainage holes. The field boreholes arrangement is shown in Figure 13.

In order to analyze the gas drainage effectiveness before and after hydraulic fracturing, the gas drainage flow and the gas drainage concentration were recorded in the No.1 borehole and the No.2 borehole until they were stable before the hydraulic fracturing. The gas drainage flow and the gas drainage concentration were also recorded in the No.1 borehole and the No.2 borehole after the hydraulic fracturing. The gas drainage flow and the gas drainage concentration of a signal borehole increased significantly after the implementation of hydraulic fracturing, as shown in Figure 14.

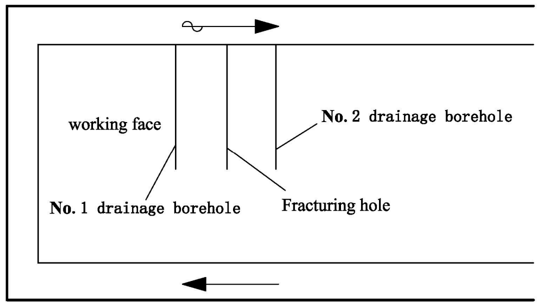
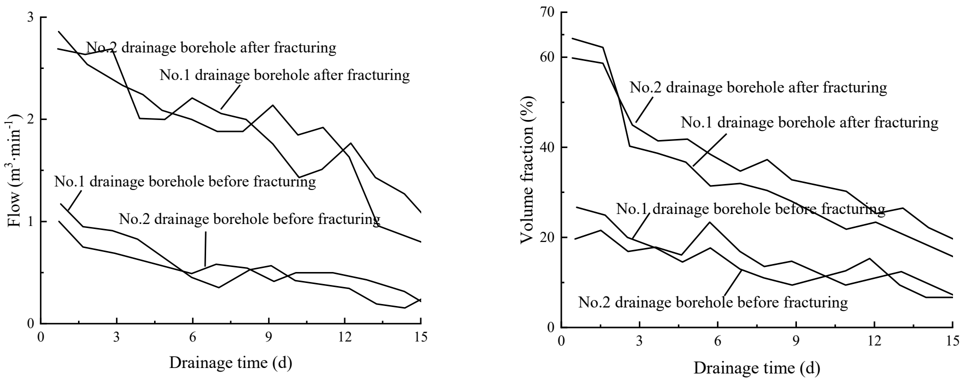


Figure 13. Field borehole arrangement.



(**a**) (**b**)

Figure 14. The comparison of gas flow and concentration before and after fracturing; (**a**) gas drainage flow; (**b**) gas concentration.

The field experiment showed that hydraulic fracturing can improve the gas drainage effectiveness, which verified the previous calculation results and the conclusion that the permeability coefficient influences gas drainage effectiveness significantly. In China, the permeability in most of the coal seams is low, and it is necessary to promote the gas drainage effectiveness by enhancing the coal seam permeability coefficient. In recent years, China's coal mines put forward a series of measures that increase coal seam permeability, such as long-hole controlling presplitting blasting technology, hydraulic fracturing, water jet slotting, and mining protective coal seam, and these measures, in practical application, proved to be feasible to improve the gas drainage effectiveness.

4. Conclusions

(1) Determined by the space shape of the gas flow field, the gas flow state surrounding the gas drainage boreholes is radial flow. According to the basic equations of radial flow, discrete equations were obtained by the implicit difference scheme, and then the gas pressure values surrounding the drainage boreholes were obtained;

(2) The gas pressure in the midpoint of two holes reflects the gas drainage effectiveness to a certain degree and declines with segmented characteristics such that the decline curve in the first period is in the form of cubic curve and the decline curve in the second period is in the form of straight line. The segmented characteristics can help predict gas pressure after a certain drainage time in a certain area surrounding the borehole;

(3) The decline rate of gas pressure has little relationship with the negative drainage pressure, and is mainly influenced by the permeability coefficient;

(4) The field experiment data verified the conclusions in this paper that it is not reasonable to improve the gas drainage volume by improving negative drainage pressure, and that enhancing the permeability coefficient can improve the gas drainage effectiveness well.

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References

1. Fan, J.; Liu, P.; Li, J.; Jiang, D. A coupled methane/air flow model for coal gas drainage: Model development and finite-difference solution. *Process Saf. Environ. Prot.* **2020**, *141*, 288–304. [CrossRef]
2. Wang, H.; Cheng, Y.; Wang, L. Regional gas drainage techniques in Chinese coal mines. *Int. J. Min. Sci. Technol.* **2012**, *22*, 873–878.
3. Li, Q.; Lin, B.; Yang, W.; Zhai, C.; Hao, Z. Gas control technology and engineering practice for three-soft coal seam with low permeability in XuanGang region, China. *Procedia Eng.* **2011**, *26*, 560–569. [CrossRef]
4. Guo, P.; Li, H.; Zhu, J. Numerical simulation of gas drainage from boreholes in coal seams. *J. Liaoning Tech. Univ. (Nat. Sci.)* **2009**, *28*, 260–262.
5. Hao, F.; Liu, M.; Sun, L. Determination method of gas drainage radius based on multi-physics coupling. *J. China Coal Soc.* **2013**, *38*, 106–111.
6. Ji, Z. *Research on Numerical Simulation about Radius of Degassing Borehole*; Henan Polytechnic University: Jiaozuo, China, 2012.
7. Teng, G.; Tan, Y.; Gao, M.; Zhao, Z. Simulation of gas drainage in fissured coal based on Lattice Boltzmann Method. *J. China Coal Soc.* **2008**, *33*, 914–919.
8. Zhou, S.; Lin, B. *Coal Seam Gas Occurrence and Flow Theory*; China Coal Industry Publishing House: Beijing, China, 1999.
9. Karacan, C.Ö.; Diamond, W.P.; Schatzel, S.J. Numerical analysis of the influence of in-seam horizontal methane drainage boreholes on longwall face emission rates. *Int. J. Coal Geol.* **2007**, *72*, 15–32. [CrossRef]
10. Packham, R.; Cinar, Y.; Moreby, R. Simulation of an enhanced gas recovery field trial for coal mine gas management. *Int. J. Coal Geol.* **2011**, *85*, 247–256. [CrossRef]
11. Deng, Q.W.; Liu, X.H.; Lu, C.; Lin, Q.Z.; Yu, M.G. Numerical Simulation of Spontaneous Oxidation Zone Distribution in Goaf under Gas Stereo Drainage. *Procedia Eng.* **2013**, *52*, 72–78. [CrossRef]
12. Zhu, W.C.; Wei, C.H.; Li, S.; Wei, J.; Zhang, M.S. Numerical modeling on destress blasting in coal seam for enhancing gas drainage. *Int. J. Rock Mech. Min. Sci.* **2013**, *59*, 179–190. [CrossRef]
13. Li, Z.X.; Lu, Z.L.; Qiang, W.U.; Zhang, A.R. Numerical Simulation Study of Goaf Methane Drainage and Spontaneous Combustion Coupling. *J. China Univ. Min. Technol.* **2007**, *17*, 503–507. [CrossRef]
14. Yang, X.; Yang, S.; Lu, P. Theoretical Calculation and Field Application on Effective Gas Drainage Radius in Borehole Along the Seam. *Saf. Coal Mines* **2013**, *44*, 5–13.
15. Zhang, X.; Ren, Z.; Mei, F. *Heat Transfer*; China Architecture & Building Press: Beijing, China, 2007; pp. 94–100.
16. Liang, B.; Yuan, X.; Sun, W. Grouped pressure test to determine effective gas drainage radius. *J. Min. Saf. Eng.* **2013**, *30*, 132–142.
17. Shi, J. Study of Gas Travel Rule and Drainage Mechanism in Coal Seams. *Coal Technol.* **2010**, *29*, 128–130.
18. Qin, D.; Zhu, H.; Zhang, M.; Shen, J.; Yang, C. Application and Research on Seam Hydraulic Fracture Permeability Improvement Technology. *Coal Sci. Technol.* **2013**, *41*, 79–81.