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Numerical Simulation of Effective Extraction Radius of Pre-Drainage Borehole Based on Coal Damage Model

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Abstract: Borehole pre-drainage is an important technical means to control a coal mine gas disaster. In order to determine the optimal pre-drainage parameters of Dashucun mine, a coal damage permeability evolution model was established based on coal damage deformation, considering gas adsorption and desorption and the Klinkenberg effect, and a damage fluid-structure coupling model of coal seam containing gas was established by combining the coal seam deformation equation and the mass conservation equation. COMSOL software was used to simulate the influence of factors such as the initial permeability of coal seam, negative pumping pressure, aperture and pumping time on the effective pumping radius of pre-drainage borehole. The results show that the effect of negative pressure on the effective extraction radius can be ignored. The effect of borehole aperture, initial permeability of coal seam and extraction time on effective extraction radius is great, which conforms to the power function relationship, and the coefficient correlation value is high. The optimal extraction parameters of Dashucun mine are determined as borehole diameter 113 mm, coal seam permeability 1×10^{-17} m^2, negative extraction pressure 30 kPa and extraction time 180 d. The research results can provide theoretical reference for the pre-drainage of gas in Dashucun mine.

Keywords: coal mine safety; gas extraction; effective extraction radius; COMSOL

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1. Introduction

Gas is an efficient and clean energy source with abundant resources in China [1]. Most deep coal seams containing gas are three soft coal seams with low permeability, which restricts the production of coalbed methane and poses a severe test to the safety and production efficiency of coal mines [2–4]. In the coal industry, coal and gas outburst is generally regarded as the biggest threat to coal mine production safety [5]. Borehole pre-drainage is one of the main measures for mine gas disaster prevention and control, and has become the main means for gas management and utilization in China [6–8]. The effective radius of borehole gas extraction is an important basis to judge the effect of coal seam drilling pre-drainage, and determining the best gas extraction parameters is an important technical means to improve the efficiency of gas extraction and reduce gas outburst.

A lot of research work has been done on the measurement of the effective extraction radius of coal seam gas. Hao et al. [9] established the gas seepage unit model around the borehole, derived the theoretical mathematical expression to calculate the effective extraction radius, and finally verified the theoretical calculation and numerical simulation results through field engineering measurement. Shang [10] used the coupled stress-seepage mathematical model of coal-bearing rocks. COMSOL multi-physical field numerical simulation software is developed for the second time. The simulation software is used to calculate the effective extraction radius corresponding to different influencing factors. Finally, the correctness of the mathematical model of gas-bearing coal and the feasibility of using the numerical simulation method to study the effective extraction radius of coal seam are proved. Pan Wei [11] established a fluid-structure coupling mathematical model considering the creep characteristics of coal based on the permeability dynamic evolution equation considering the influence of matrix contraction and effective stress. The results show that the gas extraction effect is in line with industry standards after optimizing parameters. Based on the gas flow theory of coal seam, Li [12] established the diffusion seepage continuity equation and concluded that the length of borehole had little influence on the effective extraction radius. Yuanwen Wang, Quanlin Dang, Mingsheng Duan [13–15] et al., based on COMSOL software, conducted a simulation study on the effective extraction radius of drilling through strata. The results show that the error between simulation and field measurement is small and the simulation effect is good. Hao [16] et al. established the seepage flow model of borehole drainage along the bed and studied the relationship between permeability, negative pressure and effective drainage radius, which provided an important basis for gas extraction in Huangling No. 2 Coal mine. Liu [17] et al., aiming at various problems in the measurement of the existing effective extraction radius of gas, calculated the effective extraction radius by combining extraction rate and gusher on the basis of measuring the decay law of borehole gas flow, and verified its correctness through field tests. Zou [18] et al. defined the effective extraction radius of coal seam drilling with 0.5 MPa as the boundary condition. Wei [19] established a percolation-stress coupling model based on elasticity. The research results show that the effective extraction radius increases with the increase in time, but it has a certain timeliness, and the measured results are basically consistent with the simulation results. Sang [20] established a fluid-structure coupling model through COMSOL to study the optimal hole distance of parallel drilling holes. The research results show that gas pressure decreases with the increase in extraction time, and the effective extraction radius keeps increasing. Ge [21] calculated the effective extraction radius of strata drilling in the Shigang coal industry by theoretical analysis and field test, and the problem of stuck drilling in fault construction is solved. Sun et al. [22] proposed to use the method combined with the measurement and simulation to accurately measure the effective extraction radius of the borehole along the bed, which was applied in the mine field. The test results show that the measurement period is short and the method is advanced. Wang [23] adopted COMSOL numerical simulation software to verify the effective extraction radius of common hole and hydraulic punching, and finally verified the rationality and accuracy of the field measurement method. Xu et al. [24] built a fluid-solid coupling mathematical model for coal seam gas extraction based on the fluid-solid coupling principle, carried out numerical simulation study on the effective extraction radius of coal seam gas pre-drainage borehole, and proposed an equal triangle pattern of hole distribution combined with the thickness of coal seam. After gas parameters were up to standard in field application, the hole distribution scheme was effective. Jia [25] used COMSOL Multiphysics simulation software to simulate and analyze the gas gusher rule and effective extraction radius of the borehole, and conducted field measurement verification. The numerical simulation results were consistent with the field measurement results. The effective extraction radius of coal seam is one of the important parameters to judge the effect of drilling pre-drainage gas. Zhang [26] et al. used COMSOL software to study the relationship between the effective extraction radius and extraction time, initial permeability of coal seam, negative extraction pressure and borehole aperture. Based on the gas flow theory of coal seam, Li [12] established the diffusion seepage continuity equation and concluded that the length of borehole had little influence on the effective extraction radius. Zhang [27] directly measured coal seam gas content and dynamic drilling gas extraction index using the borehole testing method, so as to determine the effective gas extraction radius of # 1 coal seam in Xima Mine. In the process of coal excavation, the internal pores and cracks are compressed. When the stress of coal rock mass reaches the yield condition, plastic deformation occurs in the surrounding rock of roadway and coal body around the borehole, and new cracks are formed and connected with each other, resulting in a sharp rise in the permeability of coal body. The models established by the above research did not consider the change of coal permeability caused by roadway excavation and drilling construction, which is inconsistent with the actual situation. Therefore, compared with the actual situation, the effective radius of gas extraction determined by the above model will have a large error.

Based on this, on the basis of previous studies, the author established a coal damage permeability evolution model based on coal rock damage deformation, considering matrix shrinkage effect, gas adsorption and desorption, the Klinkenberg effect, etc., combined with the coal seam deformation equation and the mass conservation equation to establish a coal seam damage fluid-structure coupling model. The influence of various factors on effective extraction radius in the pre-drainage process is analyzed, and the optimal gas extraction parameters are determined, in order to provide theoretical reference for the pre-drainage of Dashucun mine.

2. Fluid-Structure Coupling Model of Coal Seam Damage Permeability

2.1. Damage Permeability Evolution Model of Coal

In the process of excavation, when the stress of coal mass reaches the yield condition, plastic deformation occurs in the roadway surrounding rock and around the borehole. Based on this, an elastic strain softening model is adopted in this paper. As shown in Figure 1, the stress-strain curve can be divided into three stages: residual stress stage, plastic softening stage and elastic stage. Accordingly, the coal body around the roadway and borehole can be divided into the following four areas: raw rock stress zone, elastic zone, plastic softening zone and crushing zone [28]. The coal body in the elastic zone is in the stress state of the original rock, the force of the coal body does not change, and the gas flow in this zone belongs to the seepage zone of the original rock. In the plastic zone, the force of the coal body increases, the coal body is compressed, the pores and cracks in the coal body are closed, and the permeability is low. The gas flow in this zone belongs to the seepage shield zone. In the failure zone, the coal body has been damaged and deformed, the pores, gaps and cracks in the coal body are fully developed, the permeability of the coal body is increased, and the gas permeability of the coal body is increased to 13 orders of magnitude. The gas flow in this area belongs to the complete seepage zone.

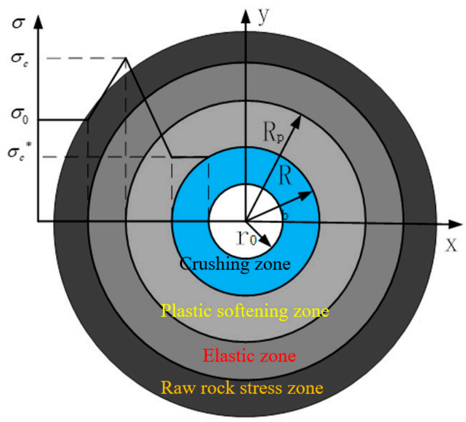


Figure 1. Elastic strain softening model and corresponding regions of the coal seam around the borehole.

The stress equilibrium state of the original coal rock mass is broken and the stress of the coal rock mass begins to redistribute when the roadway is opened in the strata. In the process of coal excavation, the internal pores and cracks are compressed. When the stress state of coal and rock reaches the damage dilatation yield condition, the surrounding rock of roadway begins to produce plastic deformation, and new cracks will be formed and connected with each other, resulting in a sharp rise in the permeability of coal. Figure 2 shows the permeability variation characteristic curve of coal during the whole process of stress and strain changes.

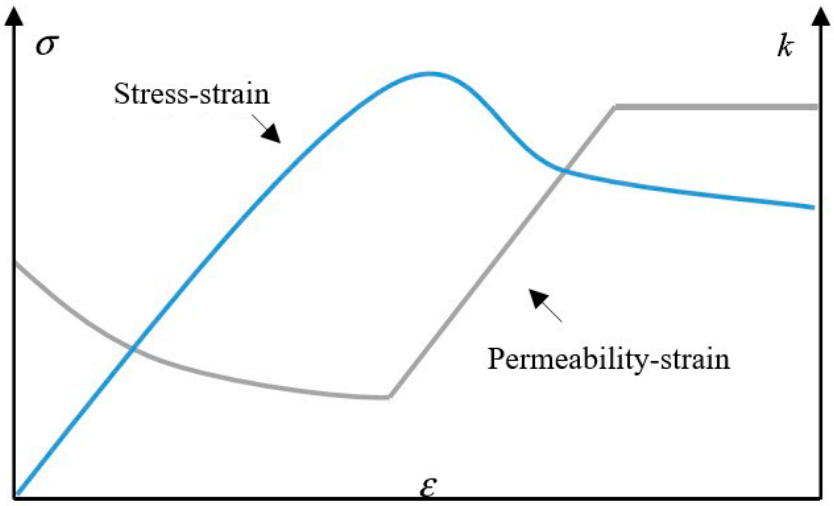


Figure 2. Permeability curve of coal during the whole process of stress and strain changes.

According to Figure 2, the permeability can be roughly divided into three stages according to the stress-strain curve, and the permeability of the coal body in different regions is different, among which the permeability of the coal body in the crushing area is the highest, while the stress area of raw rock is not affected by the excavation disturbance in the construction process of roadway and borehole, and the permeability does not change, which is the initial permeability. The first stage is the elastic stage. Before the peak stress point, the coal deformation at this stage is mainly elastic, and the permeability can be represented by the elastic model. Under the action of triaxial stress, the relationship between coal permeability and volume stress at this stage conforms to the form of exponential function [29,30]:

$$k = k_0 \exp\left\{-3C_f\left[\Delta\bar{\sigma} - \Delta p + f_m \frac{E}{3(1-2v)}\Delta\varepsilon_m^S\right]\right\} \tag{1}$$

Considering the Klikenberg effect, we can obtain:

$$k = (1+\frac{b}{p})k_0 \exp\left\{-3C_f\left[\Delta\bar{\sigma} - \Delta p + f_m \frac{E}{3(1-2v)}\Delta\varepsilon_m^S\right]\right\} \tag{2}$$

where k and k_0 are instantaneous permeability and initial permeability, mD; C_f is permeability influence coefficient, MPa^{-1}; f_m is the internal expansion ratio of adsorption deformation of matrix; $\bar{\sigma}$ is the volume stress, $\bar{\sigma} = (\sigma_1 + \sigma_2 + \sigma_3)/3$, MPa; σ_1 σ_2 and σ_3 are stresses in the direction i, j and k. ε_m^S is matrix adsorption strain.

The second stage is the plastic damage strain stage, in which both the permeability and plastic strain of coal increase, so permeability is approximately regarded as a linear increase with plastic strain. Permeability at this stage can be described as:

$$\frac{k}{k_0} = (1+\frac{b}{p})\left(1+\frac{\gamma^p}{\gamma^{p*}}\xi\right)\exp\left\{-3C_f\left[\Delta\bar{\sigma} - \Delta p + f_m \frac{E}{3(1-2v)}\Delta\varepsilon_m^s\right]\right\} \tag{3}$$

where ξ is the mutation coefficient of permeability; γ^p is the equivalent plastic strain, $\gamma^p = \sqrt{2/\left[3\left(\varepsilon_1^p\varepsilon_1^p + \varepsilon_2^p\varepsilon_2^p + \varepsilon_2^p\varepsilon_3^p\right)\right]}$, ε_1^p, ε_2^p and ε_2^p are the plastic strains in x, y and z direction; γ^{p*} is the initial equivalent plastic strain at the stage of residual stress.

The third stage is the stage of residual stress, in which the plastic deformation of coal is slow and the permeability increases slowly or even remains unchanged. Permeability at this stage can be expressed as:

$$\frac{k}{k_0} = (1+\frac{b}{p})(1+\xi)\exp\left\{-3C_f\left[\Delta\bar{\sigma} - \Delta p + f_m\frac{E}{3(1-2v)}\Delta\varepsilon_m^s\right]\right\} \tag{4}$$

To sum up, the equivalent plastic strain of coal in the first stage is 0. Although the permeability evolution is divided into three stages, it can be described by two equations:

$$\frac{k}{k_0} = \begin{cases} \left(1+\frac{b}{p}\right)\left(1+\frac{\gamma^p}{\gamma^{p*}}\xi\right)\exp\left\{-3C_f\left[\Delta\bar{\sigma} - \Delta p + f_m\frac{E}{3(1-2v)}\Delta\varepsilon_m^s\right]\right\}, & 0 \le \gamma^p \le \gamma^{p*} \\ \left(1+\frac{b}{p}\right)(1+\xi)\exp\left\{-3C_f\left[\Delta\bar{\sigma} - \Delta p + f_m\frac{E}{3(1-2v)}\Delta\varepsilon_m^S\right]\right\}, & \gamma^p > \gamma^{p*} \end{cases} \tag{5}$$

Aiming at the failure criterion of coal containing gas, DP criterion is selected this time. Under the condition of plane strain, DP criterion is combined with Mohr-Coulomb criterion plastic model. This is a choice made in order to overcome the singularity of the derivative direction of the yield surface on the cone top and the pyramid under the condition of Mohr-Coulomb, and the yield surface described by Drucker-Prager is a cone shape on the Mohr-Coulomb hexagonal cone, which is obviously the lower limit of the Mohr-Coulomb criterion. According to the specific judgment of yield, the failure equation can be expressed as cohesion and internal friction angle:

$$F = \frac{sin\varphi}{\sqrt{3\sqrt{3+sin^2\varphi}}}I_1 + \frac{3Ccos\varphi}{\sqrt{3\sqrt{3+sin^2\varphi}}} - \sqrt{J_2} \tag{6}$$

According to Pourhosseini and Shabanimashcool, the strain softening process is a process in which cohesion is lost while the internal friction angle remains constant. Assuming that cohesion decreases linearly with the equivalent plastic shear strain, the cohesion value on the entire stress-strain curve can be defined as follows:

$$c = \begin{cases} c_0 - (c_0 - c_r)\gamma^p/\gamma^{p*}, \gamma^p < \gamma^{p*} \\ c_r, \gamma^p \ge \gamma^{p*} \end{cases} \tag{7}$$

where c is cohesion, MPa; φ is the Angle of internal friction, °; J_2 is the second invariant of stress deviation, $J_2 = \frac{1}{3}I_1^2 - I_2$, I_1 and I_2 are the first invariant and the second invariant of stress tensor, Mpa.

2.2. Governing Equation of Stress Field

Based on the modified principle of effective stress in porous media and combined with gas adsorption and desorption, the governing equation of coal seam stress field modified by Navier form considering the induced volume strain of coal matrix can be obtained:

$$Gu_{i,jj} + \frac{G}{1-2v}u_{j,ji} - \beta_f p_{f,i} - \beta_m p_{m,i} - \frac{K\varepsilon_L P_L}{(p+P_L)^2}p_{,i} + F_i = 0 \tag{8}$$

where G is shear modulus, $G = D/2(1+v)$, Mpa; D is the equivalent elastic modulus, Mpa; β_m and β_f are matrix and fracture biot coefficients, respectively; p_f is fracture gas pressure, Mpa; p_m is the matrix gas pressure, Mpa.

2.3. Gas Flow Equation

There exists both adsorbed gas and free gas in the pore system of coal matrix, among which adsorbed gas is the main occurrence mode of coal seam gas, accounting for about 80–90% of the total amount. The total gas storage of coal matrix system is:

$$m_m = \rho_m \varphi_m + \rho_g \rho_c \frac{V_L p_m}{p_L + p_m} \tag{9}$$

where ρ_m is the gas density in the coal matrix, $\rho_m = \frac{M_g P_m}{RT}$, kg/m^3; M_g is the molar mass of methane, kg/mol; R is the ideal gas constant, J/(mol· K); T is the temperature of coal seam, K; ρ_c is the density of methane under standard conditions, kg/m^3; ρ_g is the density of coal skeleton, kg/m^3; V_L is Langmuir volume, m^3/kg.

Gas migration in the pores of coal matrix can be simplified as a quasi-steady state of Fick diffusion. The gas exchange capacity between matrix and fracture per unit volume of coal can be calculated as:

$$Q_s = D\sigma_c \left(c_m - c_f\right) \tag{10}$$

The change of gas volume in the matrix is mainly controlled by the gas exchange between the matrix and cracks, so the law of conservation of volume in the matrix can be described as:

$$\frac{\partial m_m}{\partial t} = -\frac{M}{\tau RT}\left(p_m - p_f\right) \tag{11}$$

Substitute Equation (9) into Equation (11), and after combination and simplification, we can get:

$$\frac{\partial p_m}{\partial t} = -\frac{V_M\left(p_m - p_f\right)(p_m + p_L)^2}{\tau V_L RT p_L \rho_a + \tau \phi_m V_M (p_m + p_L)^2} \tag{12}$$

3. Construction of Fluid-Structure Coupling Model and Boundary Conditions of Pre-Pumped Borehole

As shown in Figure 3, the finite element model is derived from the engineering simplification of a deep first coal seam in Dashu Village Mine. COMSOL is used to construct a three-dimensional finite element model of coal seam. The size of the model is 60 × 100 × 44 m, the roof and floor of 20 m thick above and below the model are breathable rocks, the middle 4 m is coal seam, and the width and height of the roadway are 3 m. The borehole is located in the middle of the coal seam, with a length of 60 m and a depth of 12 m in the sealing section. The upper part of the three-dimensional model is set as the stress boundary, and the lower part is set as the fixed boundary. Left, right, and back are rolling boundaries. The absolute pressure of roadway in coal seam is 0.1 Mpa. See Table 1 for specific parameters [31].

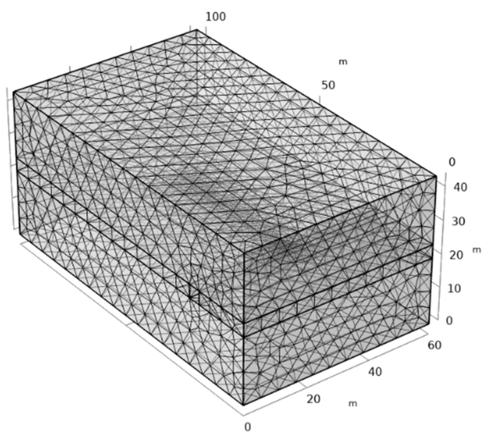


Figure 3. Finite element model.

Table 1. Simulation parameters.

Parameter Name	Numerical Value	Parameter Name	Numerical Value
Porosity	0.05	Langmuir volume product/m^3/t	41.61
Cohesion/MPa	0.8	The apparent density of coal/kg/m^3	1500
Initial permeability/m^2	1×10^{-17}	Negative pressure extraction/MPa	20
Permeability influence coefficient/MPa^{-1}	0.1	Poisson's ratio	0.35
Angle of internal friction/$^\circ$	35	The elastic modulus of coal/GPa	1
Kinetic viscosity coefficient/Pa·s	1.08×10^{-12}	Elastic modulus of coal matrix/GPa	0.8
Langmuir pressure/MPa	1.55	Initial gas diffusion coefficient/m^2/s	5.48×10^{-12}
Attenuation coefficient/s^{-1}	5×10^{-17}	Limiting adsorption deformation	0.012
Coal seam temperature/K	315.15	The Klinkenberg factor/MPa	0.76

4. Analysis of Numerical Simulation Results

Borehole pre-drainage is one of the main measures of mine gas disaster prevention and control, and has become the main means of gas control and utilization in China. The effective gas extraction radius of a borehole is an important basis to judge the effect of coal seam drilling pre-drainage. This section determines the optimal gas extraction parameters based on the influence of gas extraction parameters (negative pressure, extraction time, initial permeability of coal seam and borehole aperture) on the effective extraction radius.

It is pointed out in the Interim Regulations of Coal Mine Gas Extraction Standard that the residual gas pressure in coal seam after extraction is lower than 0.74 Mpa and is judged as the standard. Therefore, the effective extraction radius of the area where the residual gas volume in coal seam is lower than 0.74 Mpa is taken as the effective extraction radius in this paper, that is, when the gas pressure around the extraction borehole is reduced to 0.74 Mpa within a certain extraction time [23,32].

4.1. Effect of Extraction Time on Effective Extraction Radius

As can be seen from Figure 4, the effect of gas extraction time on effective extraction radius is significant. The effective extraction radius of borehole gas extraction 30 d is 0.63 m, and that of borehole gas extraction 60 d is 1.23 m, which increases the extraction range by 2 times. The effective radius was 2.57 m during 120 days of pumping, and the pumping range increased by 4 times. The effective radius was 3.79 m during 180 days of extraction, and the extraction range was increased by 6 times. The above analysis shows that the effective extraction radius increases with the increase in time.

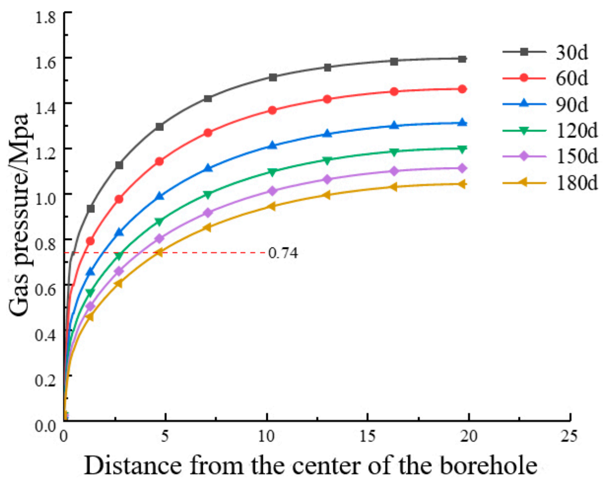


Figure 4. Matrix pressure versus time graph.

It can be seen from Figure 5 that effective extraction radius is a power exponential function relation with extraction time, and the correlation coefficient is 99.57%. The specific mathematical relation is as follows:

$$y = 0.0202t^{1.0181} \tag{13}$$

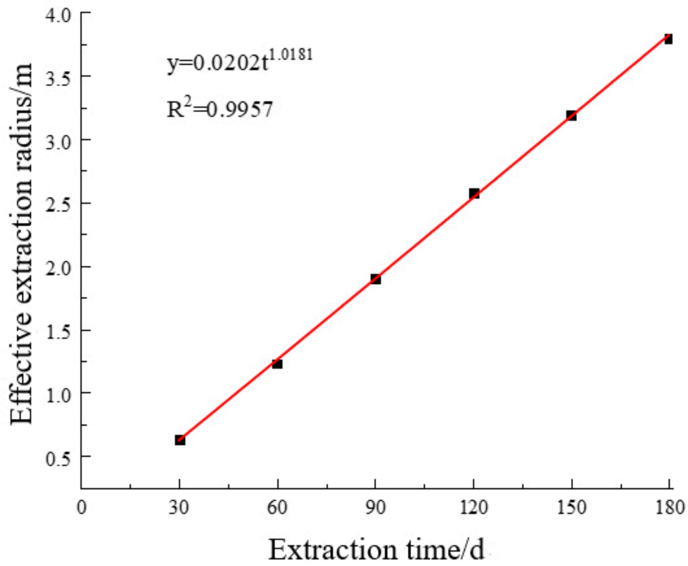


Figure 5. Fitting diagram of effective drainage radius changing with time.

4.2. Effect of Borehole Diameter on Effective Extraction Radius

The diameters of 83 mm, 92 mm, 113 mm and 130 mm were selected to study the influence of different diameters on effective extraction radius, as shown in Figure 6.

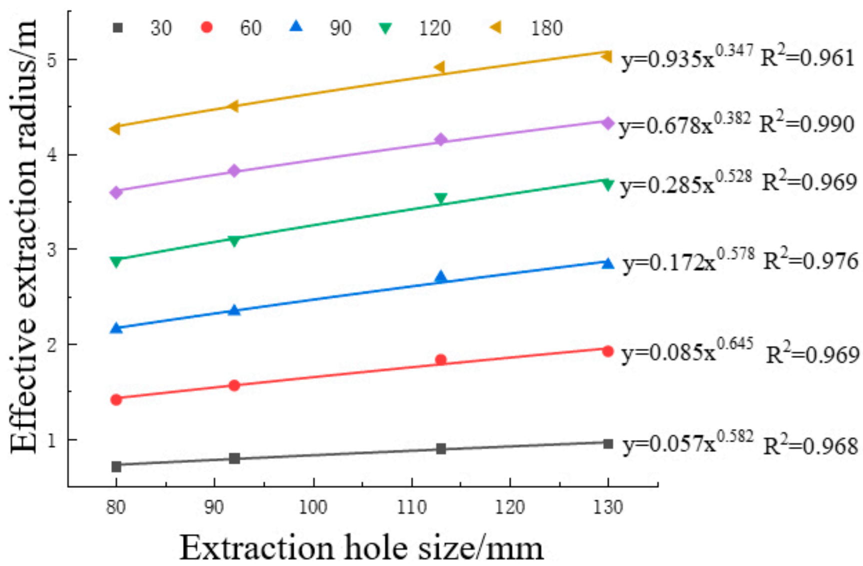


Figure 6. The relationship between the effective drainage radius and the aperture.

According to Figure 6, at 60 days of pumping, the effective extraction radius corresponding to the aperture of 83 mm, 92 mm, 113 mm and 130 mm is 1.41 m, 1.56 m, 1.83 m and 1.92 m. At 120 days of pumping, the effective pumping radius of different boreholes is 2.87 m, 3.09 m, 3.54 m and 3.68 m, respectively. Compared with 60 days of pumping, the effective pumping radius increases by 1.46 m, 1.53 m, 1.71 m and 1.76 m, respectively. The effective pumping radius at 180 days was 4.26 m, 4.5 m, 4.91 m and 5.04 m, respectively, which increased by 1.39 m, 1.41 m, 1.37 m and 0.7 m compared with the effective pumping radius at 120 days. The effective extraction radius ranges of 180 days of extraction are 0.24 m, 0.41 m and 0.11 m, respectively. According to the above analysis, the effective extraction radius of the borehole increases with the increase in the aperture in the same extraction cycle, but the increase range will gradually decrease. There is no linear relationship between the effective extraction radius of the borehole and the bore diameter. It can be seen from the fitting curve in Figure 6 that the relationship between the two conforms to the power function:

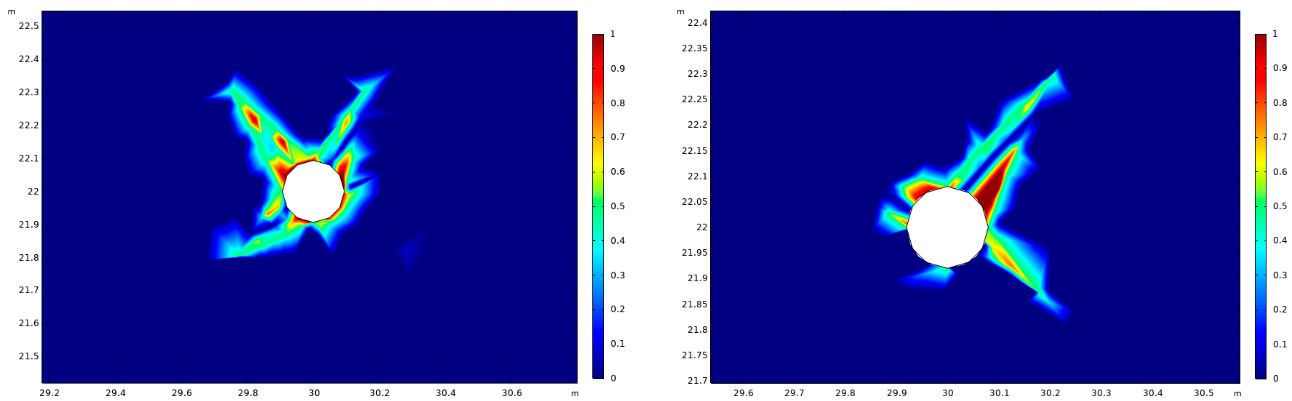
$$\begin{cases} R = 0.057d_0^{0.796} & t = 30d \\ R = 0.085d_0^{0.770} & t = 60d \\ R = 0.172d_0^{0.671} & t = 90d \\ R = 0.285d_0^{0.584} & t = 120d \\ R = 0.678d_0^{0.536} & t = 150d \\ R = 0.935d_0^{0.501} & t = 180d \end{cases} \tag{14}$$

According to Equation (14), the relationship between effective extraction radius and aperture can be written:

$$R = Ad_0^B \tag{15}$$

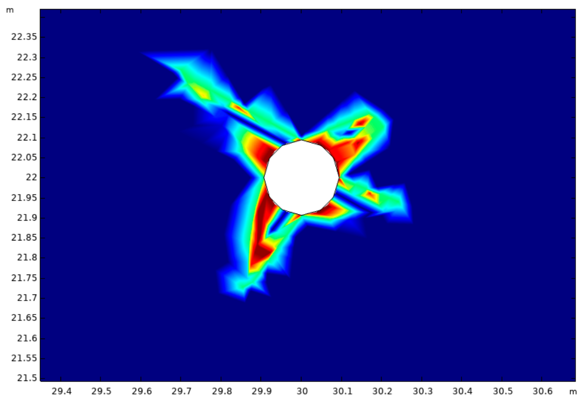
where d_0 is the diameter of drilling hole, mm; A and B are the coefficients. The value of A ranges from 0.02 to 1.0, and the value of B ranges from 0.3 to 0.7.

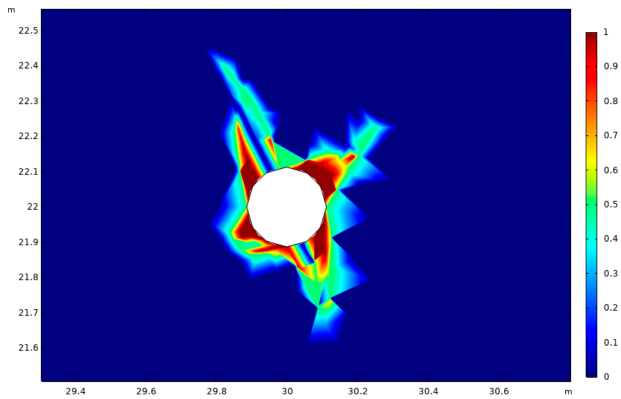
As can be seen from Figure 6, with other conditions unchanged, the slope of the relationship curve between effective extraction radius of borehole gas and extraction time increases with the increase in borehole aperture, and the effective extraction radius of borehole increases continuously. This is mainly because the stress field around the borehole will be redistributed after the excavation of the borehole. When the stress of the coal is greater than the strength of the coal, a certain plastic failure area will appear around the borehole. With the increase in borehole aperture, the coal body around the borehole is affected by drilling disturbance, and the contact area with the coal wall is also increasing. Under the action of secondary stress, a small pressure relief ring is formed, and the scope of plastic failure area around the borehole is also expanding. The damage degree of deep coal body around the borehole gradually decreases with the expansion of disturbance radius. Under the action of negative pressure extraction by borehole in the relief ring, a large amount of gas desorption makes the coal body shrink, deform and crack expand, and the permeability of coal seam improves. Figure 7 shows the plastic failure zone around the hole after drilling with different holes.



(**a**) 75 mm (**b**) 80 mm

Figure 7. *Cont.*


(**c**) 94 mm


(**d**) 113 mm

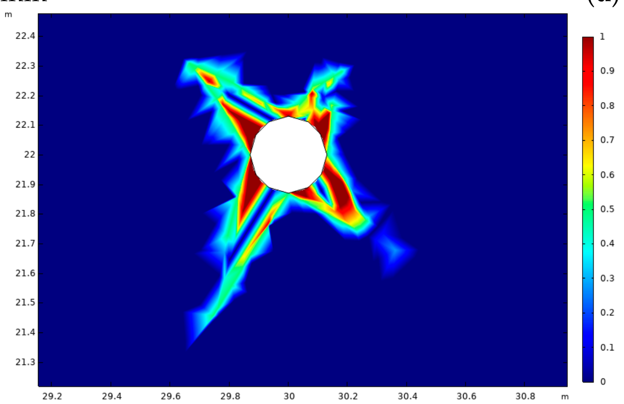

(**e**) 130 mm

Figure 7. Plastic failure around different bore holes.

When pre-drainage gas is in bedding drilling, blindly increasing the diameter of drilling will not only cause the waste of labor and material resources, but also easily increase the difficulty of drilling construction. A too large aperture will increase the possibility of coal and gas outburst and hole collapse. In summary, considering the capital and technical safety and other factors, and combined with the site construction situation, 113 mm drilling is the best choice.

4.3. Effect of Negative Pumping Pressure on Effective Pumping Radius

Negative pressures of 20 kPa, 25 kPa, 30 kPa and 40 kPa were selected to study the influence of different negative pressures on effective extraction radius, as shown in Figure 8.

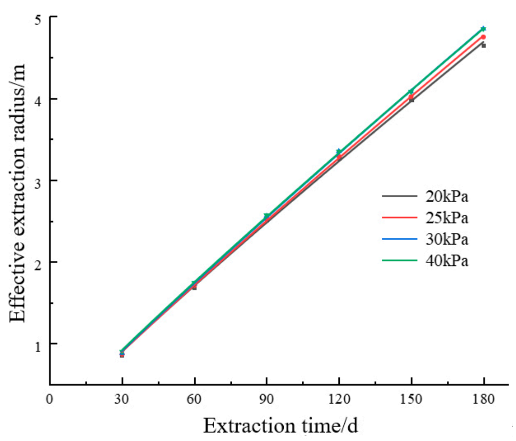


Figure 8. Variation of effective drainage radius with drainage time under different drainage negative pressures.

It can be seen from Figure 8 that the fitting curves of effective extraction radius with extraction time under different extraction negative pressures almost coincide. When the extraction time is 60 days, the effective extraction radius under the negative pressure of 20 kPa, 25 kPa, 30 kPa and 40 kPa is 1.68 m, 1.71 m, 1.73 m and 1.74 m, respectively. The effective extraction radius at 120 days is 3.27 m, 3.29 m, 3.35 m and 3.35 m, respectively. At 180 days of pumping, the effective pumping radius of 30 kPa and 40 kPa is 4.85 m, while the effective pumping radius of 20 kPa and 25 kPa is 4.65 m and 4.75 m. It shows that in a certain extraction time range, the higher the negative pressure, the larger the effective extraction radius, but the increase range of effective extraction radius is limited. The optimal extraction negative pressure of Dashucun mine is 30 kPa.

4.4. Effect of Initial Permeability on Effective Extraction Radius

The initial permeability of coal seam was set as 4×10^{-18} m^2, 6×10^{-18} m^2, 8×10^{-18} m^2, 1×10^{-17} m^2 and 1.2×10^{-17} m^2 to study the influence of initial permeability of coal seam on the extraction effect.

According to Figures 9 and 10, after 90 days of pumping, the effective extraction radius of 4×10^{-18} m^2, 6×10^{-18} m^2, 8×10^{-18} m^2, 1×10^{-17} m^2 and 1.2×10^{-17} m^2 are 1.12 m, 1.58 m, 2.1 m, 2.56 m, 2.97 m and 3.41 m, respectively. The effective extraction radius for 180 days was 2.21 m, 3.03 m, 3.92 m, 4.85 m and 5.5 m, respectively. Compared with 90 days, the effective extraction radius at 180 days increased by 1.09 m, 1.45 m, 1.82 m, 2.29 m and 2.53 m, respectively, under different permeability. At 180 days of pumping, the effective pumping radius increased by 0.89 m when the permeability was 8×10^{-18} m^2 compared with 6×10^{-18} m^2, and increased by 0.93 m when the permeability was 1×10^{-17} m^2 compared with 8×10^{-18} m^2. When the permeability is 1.2×10^{-17} m^2, the effective extraction radius is only 0.7 m higher than that of 1×10^{-18} m^2. It can be seen from the above analysis that the effective extraction radius under different permeability increases with the increase in extraction time, but the increase amplitude increases first and then decreases.

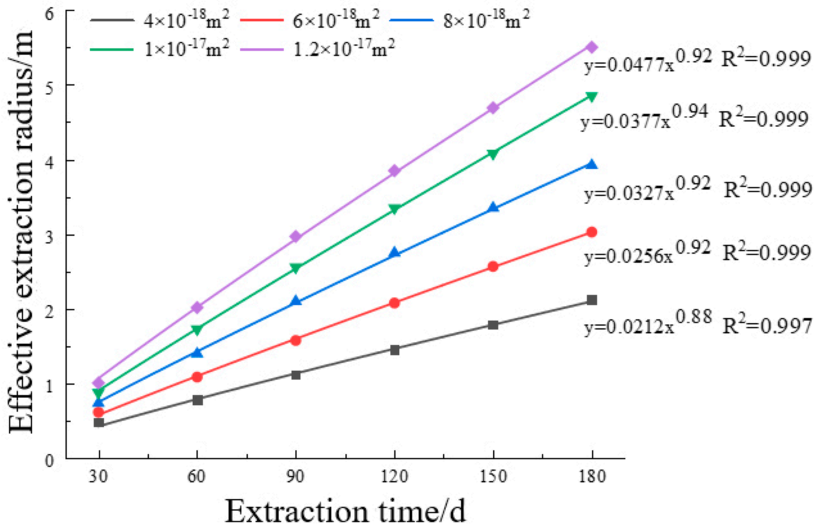


Figure 9. Variation of effective drainage radius with drainage time under different initial permeability.

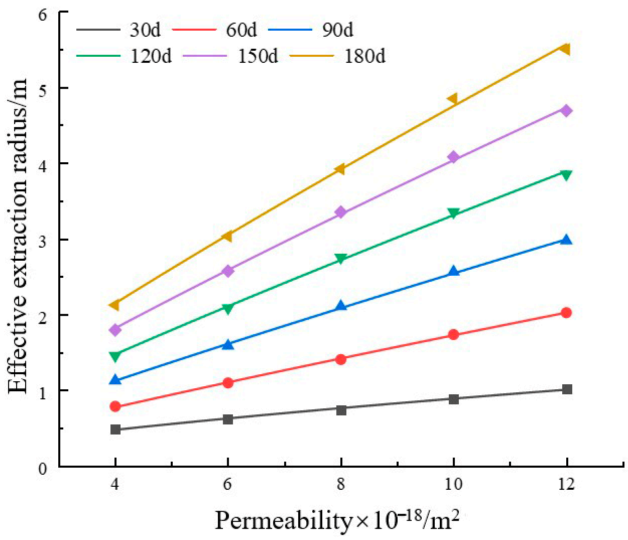


Figure 10. The relationship between effective drainage radius and permeability under different drainage time.

As can be seen from Figure 10, effective extraction radius and initial permeability are in line with the power exponent function relationship, and the correlation coefficients are greater than 0.997.

$$\begin{cases} R = 0.180k_0^{0.689} & t = 30d \\ R = 0.227k_0^{0.880} & t = 60d \\ R = 0.323k_0^{0.895} & t = 90d \\ R = 0.429k_0^{0.887} & t = 120d \\ R = 0.541k_0^{0.887} & t = 150d \\ R = 0.642d_0^{0.873} & t = 180d \end{cases} \quad (16)$$

According to Equation (16), the relationship between effective extraction radius and initial permeability can be written:

$$R = Ak_0^B \quad (17)$$

where k_0 is permeability, m^2; A and B are the coefficients. The value of A ranges from 0.18 to 0.65, and the value of B ranges from 0.6 to 0.9.

For low permeability coal seam, the permeability can be increased by pressure relief and reflection improvement, and for high permeability coal seam, the cost can be reduced by increasing the spacing of drill holes. However, considering the construction safety and other factors, the permeability of 1×10^{-17} m^2 should be selected as the best.

5. Conclusions

(1) On the basis of considering the damage deformation of coal and rock, the damage permeability evolution model of coal and rock was established considering the adsorption and desorption of gas and the Klinkenberg effect. The damage fluid-structure coupling model of coal seam containing gas was established combining the coal seam deformation equation and mass conservation equation;

(2) The effective extraction radius of pre-drainage borehole and initial permeability of coal seam, extraction time and borehole aperture are in line with power exponent function, and the coefficient correlation value is high, but the influence of negative pressure can be ignored. The longer the extraction time, the larger the borehole aperture and the higher the initial permeability of the coal seam, the larger the effective extraction radius;

(3) Based on the numerical simulation results, considering the safety of capital and technology, it is concluded that the optimal extraction parameters of Dashucun mine are

negative extraction pressure of 30 kPa, extraction time of 180 d, borehole diameter of 113 mm and permeability of coal seam of 1×10^{-17} m^2.

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