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# Permeability-increasing effects of hydraulic flushing based on flow-solid coupling

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**Abstract.** Shallow coal resources are increasingly depleted, the mining has entered the deep stage. Due to "High stress, high gas, strong adsorption and low permeability" of coal seam, the gas drainage has become more difficult and the probability of coal and gas outburst accident increases. Based on the flow solid coupling theory of coal seam gas, the coupling model about stress and gas seepage of coal seam was set up by solid module and Darcy module in Comsol Multiphysics. The gas extraction effects were researched after applying hydraulic technology to increase permeability. The results showed that the effective influence radius increases with the expanded borehole radius and drainage time, decreases with initial gas pressure. The relationship between the effective influence radius and various factors presents in the form: $y = a + \frac{b}{\left(1+\left(\frac{x}{x_0}\right)^p\right)}$. The effective influence radius with multiple boreholes is obviously larger than that of the single hole. According to the actual coal seam and gas geological conditions, appropriate layout way was selected to achieve the best effect. The field application results are consistent with the simulation results. It is found that the horizontal stress plays a very important role in coal seam drainage effect. The stress distribution change around the drilling hole will lead to the changes in porosity of coal seam, further resulting in permeability evolution and finally gas pressure distribution varies.

**Keywords:** flow-solid coupling; hydraulic flushing; stress; the effective influence radius; gas pressure

## 1. Introduction

With the increasing depletion of shallow resources, the mining has entered into the deep stage in China (Xie *et al*. 2015, Wen *et al*. 2014, 2016b). Current coal seams in China are characterized by great depth, low permeability, and strong adsorption features, and thus, the extraction of methane is relatively difficult. What's more, the coal and gas outburst is more easily induced (Hu *et al*. 2014, Wang *et al*. 2012b, Gonzatti *et al*. 2014). Therefore, the simultaneous exploitation of gas and coal was proposed to utilize these natural resources (coal and gas) safely and efficiently (Liu 2009, Wang and Cheng 2012).

For the coal seam of low permeability, the permeability should be increased firstly. The hydraulic flushing is adopted, which helps to further increase the permeability of coal seams. This

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technology is now widely used in Chinese colliery. A great number of studies have reported that the gas drainage efficiency is improved and the outburst accidents are reduced after following this technology (Chang *et al*. 2008, Liu *et al*. 2009, Yang and Wang 2010, Wei *et al*. 2010, Wang *et al*. 2011, Song *et al*. 2015, Wen *et al*. 2015, 2016a, Kong *et al*. 2016). Zou *et al*. (2015) developed a novel integrated technique (drilling–slotting–separation–sealing) for enhanced coal bed methane recovery in underground coal mines and successfully applied the technique in Yangliu colliery. Wang *et al*. (2012a) simulated the fracture evolution of coal seam after hydraulic flushing by *RFPA*$^{2D}$*-Flow* software and reported that the following four regions were formed around the borehole.

After many years of research, great progress has been made not only in hydraulic flushing technology but also coal seam gas-fluid solid coupling theory (Kong *et al*. 2016, 2017). Flow-solid coupling theory about coal and gas is mainly aimed at the gas seepage, coal solid deformation theory and their interaction. It involves gas field, stress field and crack field of multiphase medium consisting of free gas-adsorption gas-coal skeleton under Multi fields coupling effects. To solve the fluid solid coupling problem, many research works have been made by scholars both at home and abroad. The earliest study of fluid solid coupling in seepage originated from soil consolidation theory. Tetzaghi proposed the saturated soil consolidation theory and put forward the concept of effective stress, which was extended three-dimensional consolidation model later. Biot has further studied the interaction between the three-direction deformation materials and the pore pressure, and established a relatively three-dimensional consolidation theory and elastic consolidation theory of isotropic porous media. Based on coal and gas coupling model, Zhao *et al*. (1993,) established block media deformation and gas seepage coupled nonlinear numerical and physical model according to the characteristics of gas flow in coal seams and deformation. On the base of the generalized elastic visco plastic model, a coupled viscoelastic plastic constitutive equation is established for the gas bearing coal (Cao and Xian 2001). In consideration of the effects of gas adsorption to coal constitutive model, Liang *et al*. (1996) established the coupling model of coal seam gas and analyzed the influence of mining deformation to the flow regularity of coal seam gas in goaf. Wang *et al*. (2001) combined the seepage mechanics and elastic plastic mechanics, established the mathematical model of gas migration in coal seam and introduced a coupled solution method of the model according to the principle of finite element method with the consideration of the interaction between coal seam gas and coal body framework. Sun (2002) argued there is transfluence in flow of coal seam, and established the gas solid coupling theory which mutual influence of gas seepage in multiple coal seams exists. Yang *et al*. (2005) built the model of gas-solid coupling model according to the coupling effect of stress, damage and permeability evolution during the process of coal body deformation. Based on statistical damage mechanics, the coal and rock failure process was simulated in the software RFPA (Xu *et al*. 2005).

However, based on fluid and solid coupling theory, the permeability-increasing effects of hydraulic flushing have seldom been reported. In this paper, the coupling model about stress and gas seepage of coal seam was set up by solid module and Darcy module in Comsol Multiphysics. The gas extraction effects were researched after applying hydraulic technology to increase permeability. The relationship between the effective influence radius and the various factors presents in the form: $y = a + \frac{b}{\left(1+\left(\frac{x}{x_0}\right)^p\right)}$. The study will help us to further understand the flow-solid coupling theory, deeply analyze influencing factors of hydraulic flushing. Applied hydraulic flushing to the scene, it can not only increase coal seam permeability and improve the gas drainage quantity, but also decrease gas pressure in coal seam and reduce outburst danger.

## 2. Theory of flow-solid coupling

Some basic physical assumptions are introduced to establish the mathematical model of methane flow and solid coupling of coal seam: (1) Coal is porous medium and the framework of coal is elastoplasticity; (2) Coal medium saturates with single phase gas; (3) The gas flow satisfies Darcy's law in the pores, and seepage is viewed as the isothermal process; (4) The adsorption is not considered here; (5) The coal is homogeneous and isotropic; (6) The borehole is circular and vertical drills are made in coal mass.

### *2.1 Deformation control equation*

When the model occurs small plastic strains, the stress-strain relationship is then written as (Kong *et al*. 2016)

$$\sigma = \sigma_0 + C^{'} : (\varepsilon - \varepsilon_0 - \delta\theta) \tag{1}$$

where $\sigma$ is the Cauchy stress tensor, $\sigma_0$ and $\varepsilon_0$ are the stress and strain tensor, $\varepsilon$ is the total strain tensor, and $\delta$ is the thermal expansion tensor, $C'$ is the fourth-order elasticity tensor. Due to the thermal effect is neglected, $\delta\theta = 0$.

According to the deformation continuity condition, the total strain tensor is written in terms of the displacement gradient.

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{2}$$

where $\varepsilon_{ij}$ is the strain component, $u_{i,j}$ and $u_{j,i}$ denote the displacement component.

The constitutive equation of the coal deformation field is elastic-plastic constitutive equation, which incremental form is as follows

$$d\sigma_{ij}^{'} = D^{ep} d\varepsilon_{ij} \tag{3}$$

Drucker-Prager plastic yield criterion is adopted

$$F = \beta I_1 + \sqrt{J_2} - k^{'} \tag{4}$$

where $I_1$ is the first invariant of effective stress, $J_2$ is the second deviatoric stress invariant.

When matching Drucker-Prager criterion to Mohr-Coulomb criterion in 2D plane-strain applications, the $\beta$ and $k'$ is defined as

$$\beta = \frac{2\sin\varphi}{\sqrt{3}(3 - \sin\varphi)} \tag{5}$$

$$k^{'} = \frac{6C\cos\varphi}{\sqrt{3}(3 - \sin\varphi)} \tag{6}$$

where $C$ is cohesion, $\varphi$ is internal friction angle.

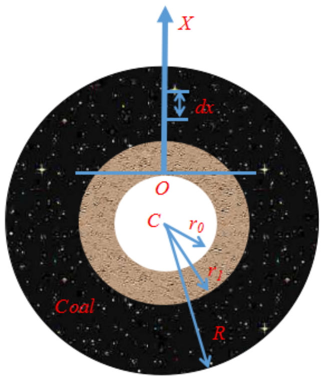



Fig. 1 Radial model of ball seepage

### *2.2 Gas flow equation*

Hydraulic flushing will cause damage to coal around the borehole, and plastic zone forms, of which fracture is well developed and the permeability is greater. Based on Darcy's law, the parameters of gas seepage were deduced.

As shown in Fig. 1, for the borehole radius of $r_0$, assuming the initial negative pressure is $p_0$ and surrounding medium is coal, the region from $r_0$ to $r_1$ is plastic zone, of which the porosity is $\phi$ and the permeability is $k$, respectively. Because of the pressure difference between the hole and the coal body, gas will penetrate into the hole. At the same time, the gas flowing into the holes was exhausted along drainage pipes. Gas reduced and pressure decreased gradually, consequently gas pressure is redistributed. Gas pressure distribution will enter a stable state when the pressure difference is not enough to make the gas flow.

As shown in Fig. 1, take the edge of borehole as the origin of coordinates. Assuming the negative pressure will not be affected by hole temperature changes and maintain a constant value. The fractures and pores will be full of methane after gas permeating.

According to Darcy's Law (Liu *et al*. 2003, Zhong *et al*. 2014), the flow rate of different percolation distance is (negative pressure in the hole)

$$u = \frac{k}{\mu}\frac{\Delta p}{\Delta x} = -\frac{k}{\mu}\frac{\Delta p}{x} \tag{7}$$

where $u$ is seepage velocity, $\Delta p$ is the pressure difference between coal body locations of $x$ and borehole, $x$ is the penetration distance, $\mu$ is gas dynamic viscosity ($1.84\times10^{-5}$ Pa·s), $k$ is the permeability (general value is $10^{-10}$~$10^{-13}$ m$^2$).

Taking a plane from the sphere and the radial flow of the sphere is simplified to two-dimensional plane radial flow

$$\frac{d^2 p}{dr^2} + \frac{1}{r}\frac{dp}{dr} = 0 \tag{8}$$

The pressure of inter-borehole and model boundary is constant. Therefore, the solution conditions are $p|_{r=r0} = p_0$ and $p|_{r=R} = p_1$. Where $p_1$ is initial gas pressure (pressure at model boundary), $R$ is the maximum radius of the seepage, $r_0$ is the radius after enlarging by hydraulic flushing, $r$ ($r_0 \leq r \leq R$) is at an arbitrary position.

### 2.3 Coupling mechanism

For deeper buried rocks, the permeability and the stress is negative exponential relationship (Sheng and Su 1998, Ye and Liu 2005).

$$k = k_0 e^{c\sigma} \tag{9}$$

where, $k$ is the permeability, $k_0$ denotes the initial permeability ($2.5e^{-12}$ m$^2$), $\sigma$ is the stress, $c$ is a constant.

$\sigma$ includes gravity of coal itself and the load of upper boundary. The internal boundary of borehole is the free boundary, which could cause the change of the stress, leading to permeability changes. Eventually, gas seepage is affected, which manifests as a trend of stress increasing and the permeability decreasing. The reason is that stress will affect the porosity, which meets the cubic law with permeability (Palmer 2009, Duan and Wang 2013).

$$k = k_0 \left(\frac{\phi}{\phi_0}\right)^3 \tag{10}$$

where $k$ and $k_0$ is permeability and initial permeability respectively, and $\phi$ and $\phi_0$ is porosity and initial porosity, respectively. Here the initial porosity is 0.0604.

Combining Eqs. (1), (7) and (9) with Eq. (10), and applying them to Comsol Multiphysics, the couple function of stress and gas could be achieved through numerical simulation.

## 3. Numerical model

### 3.1 Geometry model and boundary conditions

The 2D gas extraction model (20 m × 20 m) was established by combining solid mechanics and darcy module in Comsol Multiphysics, which can been seen in Fig. 2. In addition, the boundary conditions of model are also shown in Fig. 2. For solid module, the top boundary was applied 12.25 MPa to simulate the gravity of overlying rock seams. The bottom boundary was fixed to limit the movement, and the left and right sides were exerted roller condition to restrict the movement in horizontal direction and only allow to move in vertical direction. For darcy module, drainage pressure is 15 kPa. Other parameters need to be determined are defined in subsequent parts.

### 3.2 Initial parameters

Based on the Flow-Solid coupling theory (deformation of coal, gas diffusion and methane seepage) in Part. 2, we performed the numerical simulation of hydraulic flushing. In China colliery, gas pressure is higher than 0.74 MPa (the critical value), which indicates it might easily occur accidents, so the measures have to adopt to relieve or eliminate danger [State Regulation of Coal and Gas Outburst Prevention and Control of China (2009)]. In this simulation, we mainly study the gas diffusion effect after hydraulic flushing. Specific parameters are shown in Table 1.

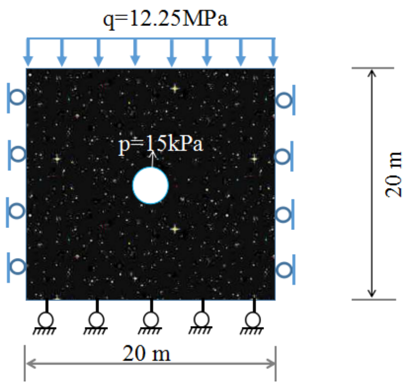



Fig. 2 Geometry model

Table 1 Parameters in this simulation

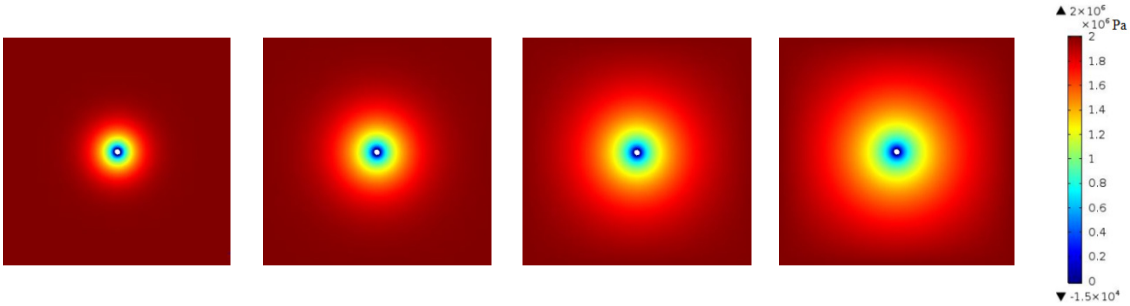
| Parameter | Value |
|---|---|
| Young's Modulus, $E$/GPa | 1.2 |
| Coal density, $\rho_c$ /(kg/m$^3$) | 1500 |
| Poisson's ratio, $v$ | 0.2 |
| Cohesion, $C$/MPa | 3 |
| Internal friction angle, $\varphi$ /deg | 32 |
| Initial porosity, $\phi_0$ | 0.0604 |
| Initial permeability, $k_0$ /(m$^2$) | $2.5\times10^{-12}$ |
| kinematic viscosity, $\mu$ /(Ns/m$^2$) | $1.84\times10^{-5}$ |
| Gas density, $\rho_g$ /(kg/m$^3$) | 0.714 |

## 4. Simulation results discussion

### 4.1 Radius of borehole

Firstly, the influence of a borehole to gas pressure relief of coal was simulated. Therefore, the radius of borehole after enlarging by hydraulic flushing was set as 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m, 0.6 m to study the effective influence radius. The standard of the effective influence radius is where gas pressure declines to 0.74 MPa. Fig. 3(a) is gas pressure distribution of 0.3 m borehole radius after drainage for 5 days. From Fig. 3, gas releasing process caused by the expanding borehole is borehole-centered, with gas flowing to the borehole along the radial direction. So the different gradient of gas pressure distribution is formed. The closer to the borehole, the greater gas pressure gradient is. This is because of the pressure relief effect of the borehole to the surrounding coal. Then the stress reduces, the corresponding permeability increases and the gas velocity rises. And the direction far from the borehole, there is the original stress zone of no disturbance and a local stress concentration area.

In order to compare the effective influence radius of different enlarging borehole radius, the effective influence radius was counted when gas flow reached steady condition, which was shown in Table 2. The effective influence radius increased with the radius of the borehole. When the




(a) Drainage for 5 d (b) Drainage for 15 d (c) Drainage for 30 d (d) Drainage for 60 d

Fig. 3 Gas distribution around borehole with drainage time

Table 2 The effective influence radius with expanded borehole radius

| Expanded borehole radius after hydraulic flushing/m | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
|---|---|---|---|---|---|---|
| The effective influence radius/m | 2.03 | 2.37 | 2.6 | 2.8 | 2.98 | 3.06 |

borehole radius was 0.5 m, the effective influence radius was up to 2.98 m. But with the borehole radius increasing, gas pressure gradient decreased gradually and the amplitude of pressure relief decreased gradually. It show that when hole radius exceeds a certain value, the effective influence radius will not increase obviously even if the radius of borehole increases. In the actual hydraulic flushing application, it exists a borehole radius that can both meet the requirements of pressure relief and saving cost.

### *4.2 Initial gas pressure of coal seam*

In the condition that the expanding radius is 0.5 m, the negative pressure in the borehole is -15 kPa, the effective permeability-increasing radius was discussed under different initial gas pressure. The initial gas pressure was designed between 0.8 MPa to 1.2 MPa, and gas pressure was plotted in Fig. 4. The effective influence radius under different initial gas pressure was analyzed, shown in Table 3. The higher the initial gas pressure of coal, the smaller unloading pressure range was when pressure relief reached stable stage. When the initial gas pressure was 0.8 MPa, the effective influence radius was 5.58 m, which might be because the initial gas pressure is very close to 0.74 MPa and gas pressure could be reduced below outburst line easily. With the increase of the initial gas pressure, the effective influence radius changed slowly. Under the constant gas pressure, with the increase of the distance from the borehole wall, the gradient of the gas pressure decreased gradually and finally tended to be gentle.

### *4.3 Drainage time*

In order to study the effects of drainage time to the distribution of gas flow field, the gas pressure contour of 5 days (4.32e5 s), 15 days (1.296e6 s), 30 days (2.592e6 s), 60 days (5.184e6 s) were selected, which were shown in Fig. 3. From Fig. 3, gas pressure around the drilling hole increased along the radial direction gradually away from the center of the hole. With the increase of drainage time, the influence range of gas pressure expanded gradually. Because the pressure of

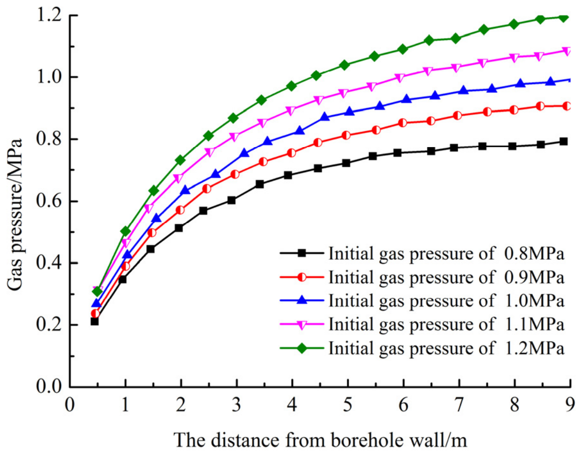



Fig. 4 Gas pressure curve of different initial gas pressure

Table 3 Effective radius of influence under the different initial gas pressure

| Initial gas pressure/MPa | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 |
|---|---|---|---|---|---|
| The effective influence radius/m | 5.58 | 3.79 | 2.98 | 2.43 | 2.06 |

inter-borehole was negative in the process of extraction, the original coal seam gas pressure of 2 MPa distributed uniformly in coal seam. Borehole wall was the first to be affected after drilling. With the release of gas around the borehole, gas pressure decreased gradually and pressure difference formed, further leading to gas seepage.

To reflect the change of gas pressure gradient, the horizontal line on the right side of borehole was selected as the research object. Gas pressure values of 10 days, 15 days, 20 days, 30 days, 60 days were selected, and the gas pressure curves at different times were drawn (Fig. 5). It could be obtained that gas pressure reduced more with longer drainage at the same distance away from the

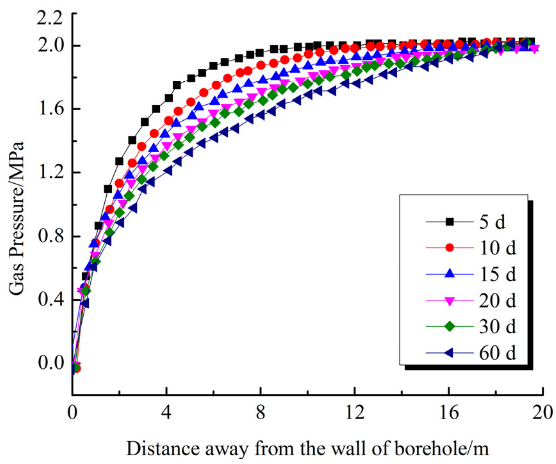



Fig. 5 The curve of gas pressure under different drainage time

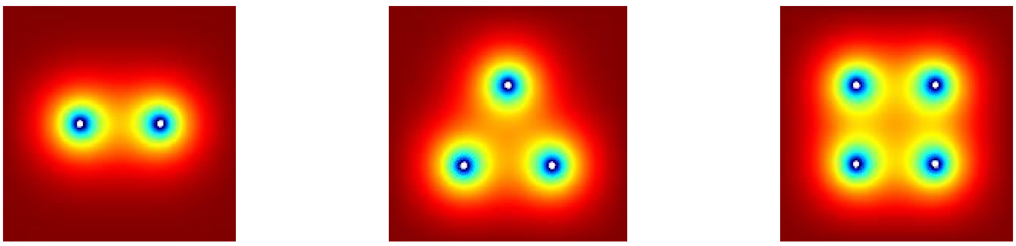
Table 4 Effective influence radius with days

| Day/d | 5 | 10 | 15 | 20 | 30 | 60 |
|---|---|---|---|---|---|---|
| The effective influence radius /m | 0.9 | 1.1 | 1.2 | 1.35 | 1.60 | 2.01 |

borehole. Drainage for the same days, gas pressure gradient changed slowly from borehole wall to the depth of the coal, eventually tends to 0. Gas pressure gradient decreased gradually with the drainage time, but the change range of gas gradient increased, which is why gas drainage volume reduced gradually with the drainage days in the field. The pressure relief process was affected from the borehole center to around, so the pressure difference on drilling wall was larger and gas pressure gradient was obvious at the beginning stage. Borehole pressure relief leading to stress re-distribution around coal, and borehole wall is the first to be affected after drilling. Plastic damage area expanded gradually, thus the fracture ratio and porosity in failure zone increased and the mobility of gas enhanced. With increasing time, the cracks propagated, coalesced and developed into the deep part of the coal under the role of stress. So the influence range of gas pressure also extended to the deep part. After gas pressure was stable, the effective influence radius of the different drainage days was counted, as shown in Table 4.

### *4.4 Arrangement of boreholes*

After hydraulic flushing, the effective influence radius of 0.5 m borehole radius was up to 2.98 m, indicating that the effect of hydraulic flushing pressure relief is better, which could be used to reduce gas pressure in mine engineering to ensure the safety in mining. In practice, a lot of drilling holes should be arranged in a drilling site to achieve the purpose of pressure decline. According to the spatial position of the drilling hole, it was divided into three kinds of hole-setting pattern: “straight line”, “triangle”, “rectangle”. Under the condition that the radius was 0.5 m, the negative pressure was -15 kPa and the initial gas pressure was 2 MPa, the effects of pressure relief and the effective influence radius of different borehole arrangement modes were discussed. The cloud images of gas pressure relief effect of basic units about the three borehole modes were shown in Fig. 6. The center distance of the drilling holes was shown in Table 5.



(a) Line type (b) Triangle type (c) Rectangle type

Fig. 6 The effects of gas relief under different hole arrangement

Table 5 The distance between center of holes

| Arrangement mode of boreholes | Straight line | Triangle | Rectangle |
|---|---|---|---|
| The center distance/m | 10 m | 11 m | 10 m |

Fig. 6 showed the pressure relief effects of basic unit about different borehole arrangement method. The effect of pressure relief was better than that of single hole, and the different combination is not a superposition of single hole. The influence range of the drilling hole is enlarged because of the mutual influence between the holes, and different combination center distance of the drilling hole is 10 m or more. So the average effective pressure relief radius of the single hole would reach above 5 m. In actual mining process, different combinations could be adopted according to the specific circumstances of the mine geological conditions to achieve a safe, efficient and cost-saving effect.

## 5. Field application

In order to verify the validity of the simulation results, the test was carried out in 1063 machine pumping lane in Huaibei mine for the field application. 1#-4# piezometric holes were drilled next to the drainage borehole, 4 m, 5 m, 6 m and 7 m away from the drainage hole respectively. And drainage holes were constructed a period of time after pressure holes were finished and pressure was stable. The drainage had lasted for two months and the change of gas pressure in drainage holes were recorded. From the data recorded, the initial gas pressure of 1# and 4# was 2 MPa, the 2# and 3# was 1.5 MPa. The curves of gas pressure change of 1#-4# boreholes in 60 days were shown in Fig. 7. It can be seen that the gas pressure in 1# borehole reduced 50% within 4 days, and 2#, 3#, 4# piezometric holes within 18 days, 53 days, 51 days, respectively, indicating that the closer to drainage holes, the more serious coal deformation and damage would be. And the increase of porosity and the permeability is larger, leading to gas pressure dropping faster. For 1#, 2# and 4# borehole in the initial stage of drainage, the gas pressure gradient were all larger and gas pressure dropped faster, but the gas pressure gradient became smaller with drainage time. However, gas pressure in 3# borehole increased firstly, and then began to decline when it reached to 1.8 MPa. This was because that stress relief zone, stress concentration zone and original stress area formed around the hole after stress relief. And 3# piezometric holes might be just in the area of stress concentration, resulting in temporary accumulation of gas in this region, so gas pressure in 3# pressure borehole increased firstly and then decreased.

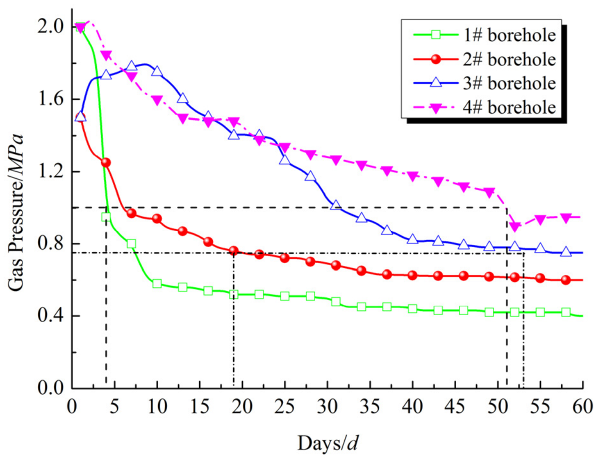
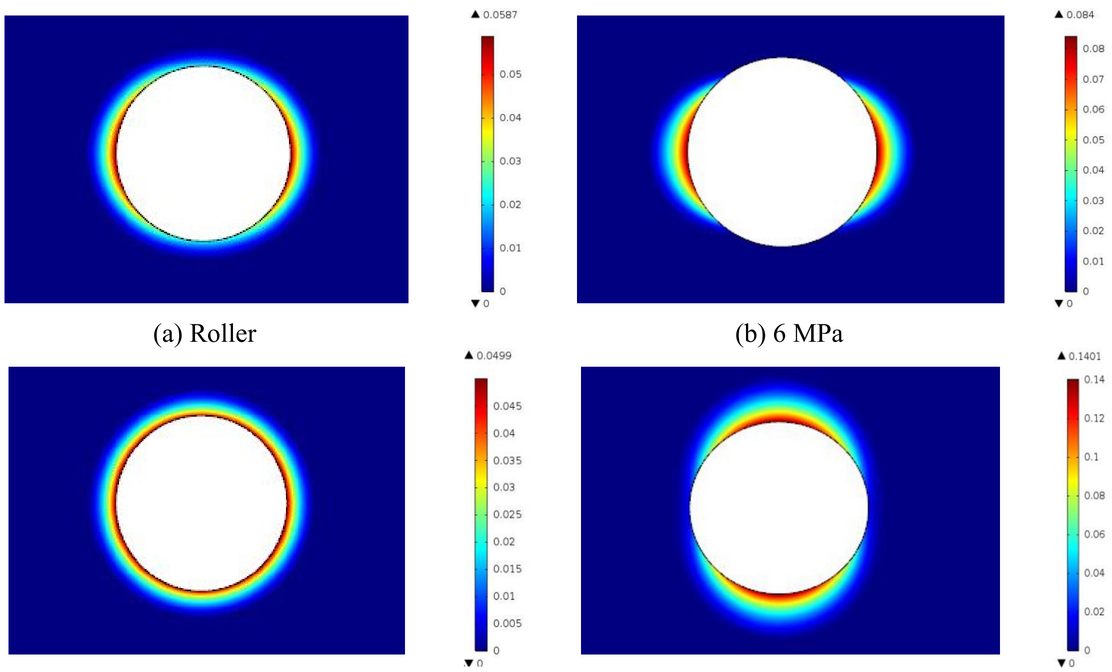



Fig. 7 Gas pressure of hole varies with time

## 6. Discussion

### *6.1 Plastic deformation around the borehole*

After drilling in coal seam, the stress of overlying coal and rock transfers to the sides of coal boreholes. Elastic deformation of the borehole wall would occur due to the stress. The borehole wall firstly enters into the plastic failure stage and elastic-plastic changes extend to the depths of the coal along the radial direction of the borehole. In this simulation, the changes of plastic failure zone around borehole were studied with the sides boundary at roller condition, the stress of 6 MPa, 12.55 MPa and 18 MPa. As the drilling radius is smaller than the entire model, the plastic zone around the borehole was enlarged in order to be more clearly observed, as shown in Fig. 8. It could be seen when roller boundary is applied in both sides of the model, the plastic range of borehole in horizontal was larger than it in the vertical direction. This was because the upper load transferred to the sides of the borehole, which had a greater influence on horizontal direction. When a horizontal stress of 6 MPa was applied to both sides of the model, the plastic zone in horizontal was particularly evident, while there was almost no plastic zone in the vertical direction. The constraint from the horizontal prevented the coal extending to the horizontal direction to release the accumulated elastic energy, so the plastic deformation in horizontal direction was more significant. When applied to the horizontal stress of 12.55 MPa, uniform plastic deformation around hole occurred, this was because the horizontal stress was equivalent to the top load. The lateral pressure coefficient was 1 and the borehole is in stress balance, so deformation in each direction was similar. When the horizontal stress of 18 MPa was applied to both sides of the model,




(a) Roller (b) 6 MPa

(c) 12.55 MPa (d) 18 MPa

Fig. 8 The plastic zone of coal

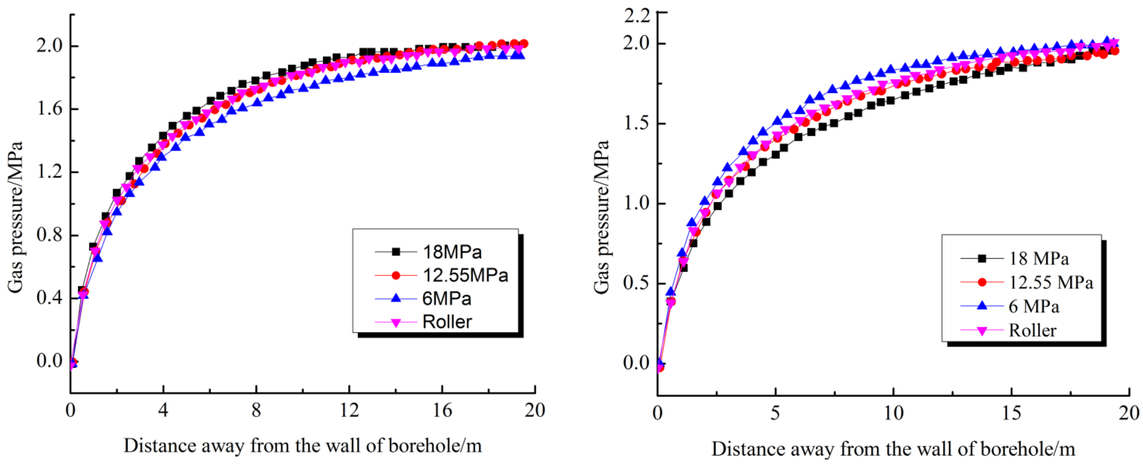
the vertical plastic of the borehole was more obvious. This was because with respect to the top load 12.55 MPa, the horizontal stress played a leading role, which was just the opposite to the situation of 6 MPa. In actual coal seam mining, similar phenomenon may appear if there is a larger structure stress in front of boreholes, such as roadway floor heave and roof destruction.

### 6.2 Gas pressure under different horizontal stress boundaries

In the actual mining, faults, folds and other geological structures would appear in drilling, then tectonic stress would form in both sides of the borehole. This phenomenon can be simulated by applying horizontal stress on both sides of the model. On the boundary stress of 6 MPa, 12.55 MPa, 18 MPa and roller boundary, gas pressure change on the right side and top side of the borehole was studied at the same drainage days. Figs. 9(a) and (b) showed the gas pressure difference. From Figs. 9(a) and (b), the higher horizontal stress applied was, the smaller the influence scope of gas pressure. This was because the greater horizontal stress plays a leading role and has a greater effect on borehole wall. The plastic deformation up and down of the borehole was significant with full crack propagation and coalescence rate, so the change of gas pressure in the vertical direction became more obvious. But gas pressure curves for the 12.55 MPa and roller boundary almost overlapped. According to plastic deformation of boreholes in Figs. 8(a) and (c), plastic changes of roller boundary and 12.55 MPa stress in horizontal direction seemed similar. On the vertical direction, the plastic zone of 12.55 MPa horizontal stress was larger than that of roller boundary, but gas pressure curves also almost overlapped, which might be because plastic range was too small with inapparent fracture and porosity rate.

### 6.3 The Effective influence radius

According to the simulation results of Part 4.1-Part 4.3, the data of Table 2-4 was fitted to show in Figs. 10(a)-(c). From Fig. 10, the effective influence radius with factors such as radius of borehole, initial pressure and drainage time present in the following form. The fitting degrees were all above 99%, showing that the fitting effect was very good.



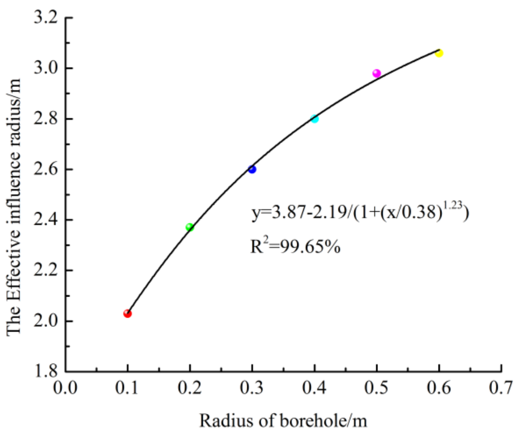

(a) Horizontal direction (b) Vertical direction

Fig. 9 Gas pressure

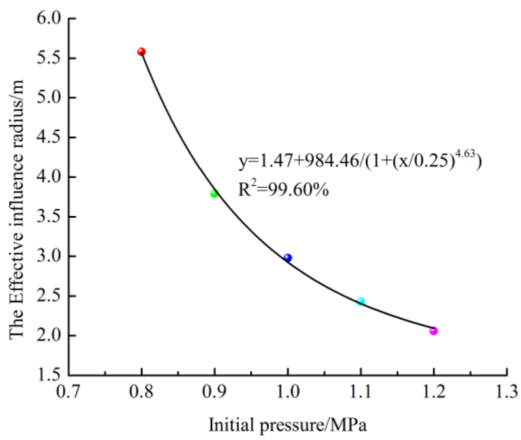
$$y = a + \frac{b}{\left(1 + \left(\frac{x}{x_0}\right)^p\right)} \tag{11}$$

where $y$ denotes the effective influence radius; $x$ is independent variable which can be radius of borehole, initial pressure, drainage time and so on; $a$, $b$, $x_0$, $p$ are constant.

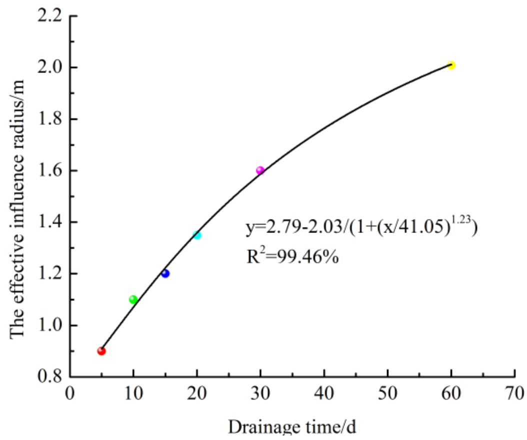
In the actual production of mining, gas and geological conditions should be determined firstly. Then the drainage effect will be simulated by Comsol Multiphysics. The limited data is fitted to deduce a general formula about the effective influence radius of the coal seam at the same conditions of the mine, which will be promoted and applied. In terms of the reasonable effective influence radius of the final determination, the design of the drilling program will be carried out for the gas pre-drainage. This can not only reduce drilling costs, but also achieve the best results in limited time. At the same time, it can also reduce the outburst danger of coal seam and ensure the safety of subsequent coal seam mining.




(a) Radius of borehole




(b) Initial pressure




(c) Drainage time

Fig. 10 The effective influence radius with factors

## 7. Conclusions

- Coupling effect of stress and gas pressure plays a significant role on coal and gas outburst. And for low permeability coal seam, hydraulic flushing can cause stress re-distribution in coal seam and the increase of porosity and permeability in plastic failure area.
- After drilling in coal seam, gas pressure forms the concentric rings centering at the borehole. The influence scope of gas pressure enlarges with the drainage time. At the same distance away from the borehole, gas pressure reduces more with longer drainage days. With the same days of drainage, gas pressure gradient slows gradually from borehole wall to the depth of the coal body, and finally tends to 0.
- The bigger borehole radius after hydraulic flushing is and the lower innitial gas pressure is, the better gas pressure relief effect will be. The effective influence radius increases with the pressure relief time, but the amplitude decreases gradually, and finally tends to be stable. The influence range of multiple borehole is larger than that of the single hole, and the interaction between the holes could enlarge the gas pressure relief radius. Besides, average effective radius of a single hole under different distribution ways will reach 5 m or above.
- In the actual mining process, three kinds of borehole-setting patterns such as “straight line”, “triangle”, “rectangle”, are determined according to specific geological conditions. The appropriate and economical pattern will be selected.
- In the coal seam drilling model, the horizontal stress plays a leading role with serious deformation forming on the up and down side of borehole. Due to it, roof fall and floor heave forms in coal and rock roadway. If it is the top load that plays a leading role, the effect will be opposite, which is the reason of roadway wall spalling. Uniform deformation and destruction around boreholes will appear if the top load and horizontal pressure are equal.

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