Numerical Simulation on Gas Drainage of Boreholes in Coal Seam Based on Gas-Solid Coupling Model

Bo Li[1, 2]* Jianping Wei[1], Peng Li[3]

[1]*State Key Lab Cultivation Base, Henan Province Key Lab of Gas Geology & Gas Control, Henan Polytechnic University, 2001 Shiji Road, Jiaozuo, Henan, China*
[2]*Henan Key Laboratory of Biogenic Traces & Sedimentary Minerals, 2001 Shiji Road, Jiaozuo, Henan, China*
[3]*Faculty of Resource and Safety Engineering, China University of Mining & Technology (Beijing), Ding 11 Xueyuan Road, Haidian District, Beijing, China*

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Abstract

Gas pre-drainage of boreholes in coal seam is considered to be the main effective measure for preventing coal and gas outbursts. In order to research the stress changes in surrounding coal mass of drainage boreholes and the distribution of pore pressure, as well as the evolution of permeability, the methane in surrounding coal mass of boreholes was classified into two different parts, namely free gas and adsorbed gas, which were based on the law of mass conservation. Then the gas migration model of coal mass around boreholes was proposed considering the Klinkenberg effect. The deformation field equation and gas seepage equation of coal seam were deduced, and the evolution models of permeability and porosity were derived under the combined contribution of the adsorption swelling and pore-fracture compression. Afterwards, the fluid-solid coupling model was imported on the basis of the basic theory of porous media fluid-solid coupling, and the two-dimensional geometric model was implemented into the multi-physical coupling simulation software. The conclusions were obtained as follows: (1) The initial stress state was disturbed due to the presence of drainage boreholes, and the concentrated stress in the coal mass around boreholes was gradually transferred into the deep zone, which was consistent with the evolution of permeability; (2) As time goes by, the gas drainage radius gradually increased, however the growth rate reduced by degrees.

Keywords: Coupling model; Drainage borehole; Numerical simulation; Permeability, Gas pressure

1 Introduction

Due to the increase in the level of mechanization and the mining scale, the mining depth raises along with the exhausting shallow resources of old mines. As the new mines mainly locate in deeper coal field, gas content and gas pressure of coal seam increases gradually. Therefore, the working face is more susceptible to unusual gas emissions and coal and gas outbursts. As we all known, gas pre-drainage of boreholes in coal seam is the main measure for preventing coal and gas outbursts. During the drainage process, the change of permeability in coal seams is a very complex coupling between gas migration and coal deformation. There are a large number of previous studies by many domestic and foreign scholars. Yang et al. [1-2] investigated the relief-gas drainage of coal seam by solid-gas coupling model of the coal containing gas, considering the role of the adsorption and desorption in coal seam. Ying et al. [3-4] induced the solid-gas dynamic coupling model of the coal containing gas, with the introduction of expansion stress due to gas adsorption based on the consideration that the coal and rock mass is isotropic elastic-plastic medium. Xiao and Pan [5] presented the percolation model of coal-bed gas considering the slippage effect and simulated the coal-bed gas migration law. Zhao et al. [6-7] derived the gas flow mathematical model of homogeneous coal seam under the solid-gas coupling action. Liang et al. [8] proposed a mathematical model of coal and gas coupling considering the influence on coal mass constitutive relation of gas seepage in the temperature field. Bai [9] developed the mathematical model of gas flow in coal seams, regardless of stress and temperature, and simulated the gas flow of borehole. Si et al. [10] proposed gas fluid solid coupling equations using the basic theorem of porous media seepage and the basic theory of fluid solid coupling, simulated and analyzed the regulation of gas migration along the drainage borehole. Ding et al. [11] established the mathematical model of borehole gas flow equation on the basis of coal seam gas flow theory and the law of mass conservation, regarding the gas flow field around the hole in coal seam as the research object. Based on this model, the numerical simulation was carried out, and the actual drainage was compared and analyzed, then the gas drainage parameters suitable for the coal mine were obtained. Based on the previous research, the fluid-solid coupling model for gas was established by using the basic theory of fluid-solid coupling of porous media, and with the multi physics coupling simulation software, two-dimensional geometric model was numerically calculated. Then the distribution of pore pressure and the evolution

*Corresponding aouthor's E-mail: anquanlibo@163.cn

of permeability with the stress variation of coal mass around the borehole under the drainage conditions were simulated on the basis of the relevant parameters actual of coal mine.

2 Fluid-solid Coupling Model

2.1 GOVERNING EQUATIONS OF GAS FLOW

Assuming that the coal is considered to be a homogeneous isotropic medium, the methane is a kind of ideal gas and the gas seepage in coal and rock mass is isothermal. The methane in coal seam is composed of adsorbed gas and free gas, and gas migration in coal seam follows Darcy law.

Considering the Klikenberg effect, the gas flow equation of coal mass around the boreholes according to the mass conservation law [12] can be expressed as [13]:

$$2\left(1-\frac{1-\varphi_0}{1+\varepsilon_v}+\frac{abcp_0}{(1+bp)^2}\right)\frac{\partial p}{\partial t}+2p\frac{1-\varphi_0}{(1+\varepsilon_v)^2}\frac{\partial \varepsilon_v}{\partial t} -\nabla\cdot\left[\frac{k}{\mu}\left(1+\frac{m}{p}\right)\cdot\nabla p^2\right]=Q_q \tag{1}$$

where φ_0 is the initial porosity, ε_v is the volumetric strain of the coal, a is the ultimate adsorption amount of the coal for unit mass (m^3/t), b is the adsorption constant of the coal (MPa^{-1}), c is the rectified parameter of the coal (kg/m^3), p_0 is the standard atmospheric pressure (Pa), p is the gas pressure of the coal (Pa), t is the time (s), k is the permeability of the coal (m^2), μ is the dynamic viscosity of the gas (Pa·s), m is the gas content of the coal (kg·m^{-3}) and Q_q is the source term (kg·m^{-3}·s^{-1}).

2.2 DYNAMIC EVOLUTION MODEL OF POROSITY AND PERMEABILITY

During the process of drilling, the basic balance of initial rock stress field and gas pressure field around the borehole is broken, and the stress around the borehole redistributes, leading to the changes in pore structure of coal mass. Combined with the definition of volume strain of coal mass due to the deformation, the dynamic evolution equation of porosity for coal mass [14,15] can be obtained, considering the absorption expansion and pore compression, shown as follow:

$$\varphi=1-\frac{1-\varphi_0}{1+\varepsilon_v}\left\{\begin{array}{l}1-K_Y(p-p_0)+\\ \dfrac{2a\rho RTK_Y[\ln(1+bp)-\ln(1+bp_0)]}{9V_m(1-\varphi_0)}\end{array}\right\} \tag{2}$$

where, φ_0 denotes original porosity, K_Y is the volume compression coefficient (MPa^{-1}), V_m is the molar volume of gas, V_m is equal to 22.4×10^{-3}m^3/mol, R is the universal gas constant, and equal to 8.3143 J/(mol·K).

Previous studies are shown that, the relation between the porosity and permeability [16] obeys an exponential function as follow:

$$k_g=k_{g0}\exp[22.2(\varphi/\varphi_0-1)] \tag{3}$$

where, k_{g0} is the permeability under the stress of zero(m^2); k_g is the permeability under the stress of non-zero（m^2）.

Substituting Eq.(2) into Eq.(3), the evolution equation of permeability considering adsorption expansion and pore compression can be obtained as follow:

$$k_g=k_{g0}\exp\left[22.2\left(\begin{array}{l}1-\dfrac{1-\varphi_0}{1+\varepsilon_v}\\ \left\{\begin{array}{l}1-K_Y(p-p_0)+\\ \dfrac{2a\rho RTK_Y[\ln(1+bp)-\ln(1+bp_0)]}{9V_m(1-\varphi_0)}\end{array}\right\}/\varphi_0-1\end{array}\right)\right] \tag{4}$$

2.3 DEFORMATION GOVERNING EQUATIONS OF COAL AND ROCK MASS CONTAINING GAS

The skeleton deformation of coal mass under load follows the principle of Terzaghi effective stress, differential equation of stress equilibrium can be indicated with effective stress, as expressed by [17]:

$$\sigma_{ij}=\alpha p\delta_{ij}+(\sigma_e)_{ij} \tag{5}$$

where, $(\sigma_e)_{ij}$ is the effective stress tensor for coal and rock mass containing gas, σ_{ij} is the total stress tensor for coal and rock mass containing gas, δ_{ij} is Kronecher function.

The relation between strain and displacement of coal and rock mass is written with the type of geometric equation as follow:

$$\varepsilon_{ij}=\frac{u_{ij}+u_{ji}}{2} \tag{6}$$

where, ε_{ij} is the strain tensor of coal seam，u_{ij} and u_{ji} are the displacement components of coal mass.

Because the coal and rock mass are assumed to be homogeneous and isotropic elastic, so it meets the following deformation constitutive relationship of coal and rock mass containing gas as a function of the stress tensor, strain tensor and pore-fluid pressure [18]:

$$2G\varepsilon_{ij}+\lambda\delta_{ij}\varepsilon_v-\alpha p\delta_{ij}+F_i=0\ (i,j=1,2,3) \tag{7}$$

where, λ is Lame constant, G is shear modulus, F_i is volume force(N/m^3).

Incorporating with Eqs.(1), (4), (5), (6), (7), the governing equations of solid-gas dynamic coupling model for the gas in the surrounding coal mass of borehole can be induced, utilizing the basic theory of fluid-solid coupling of porous media. The function implies the interaction of coal mass and gas with considering the dynamic changes of porosity and permeability of coal mass and the gas seepage characteristics. The governing equations of solid-gas dynamic coupling model for gas in surrounding coal mass of borehole and the initial conditions and the boundary conditions given through specific problems, constitute the solid-gas coupling model of coal and gas.

3 Calculation model

3.1 GEOMETRIC MODEL

Based on the coupling model induced by the previous theories, a two-dimensional plane model can be adopted in the numerical simulation of borehole drainage. The model is shown as Figure 1. The height of model (the thickness of coal seam) is assumed as h=6 m, the length is assumed as L=40m, the radius of borehole is assumed as r=94mm, the bottom of the model is fixed, and the left and right boundaries are set as free. The total stress of overburden rock stratum about 13.5MPa is applied on the model, the negative drainage pressure is assigned to 13kPa, and gas pressure of coal seam is 1.2MPa. The borehole locates in the middle of the model. The main physical parameters of coal seam are listed in Table 1. In this respect, the direction of y axis is assumed as that of height, and the direction of x axis is assumed as that of length. The grid of model is fined as shown in Figure 2.

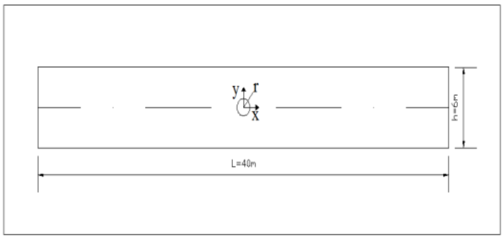


FIGURE 1 Model of drainage borehole

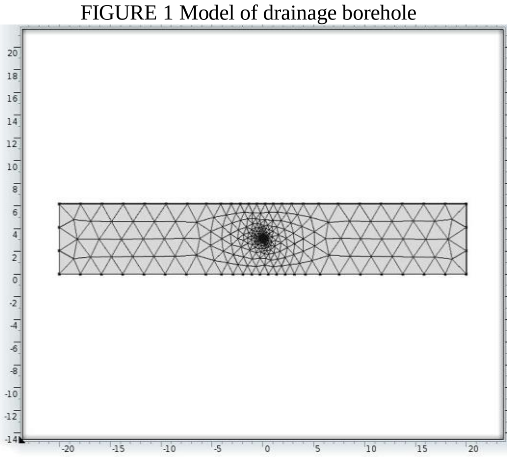


FIGURE 2 Model meshing figure of single drainage borehole in homogeneous coal seam

TABLE 1 Associated parameters used in numerical simulation

Parameters	Unit	Value
Klikenberg's coefficient, *m*	Pa	**0.251**
Biot's coefficient, *α*		**0.801**
Coal density, ρ_s	kg/m^3	**1400**
Initial porosity of coal, φ_0		**0.0286**
Methane dynamic viscosity, *μ*	Pa·s	**1.08×10^{-5}**
Langmuir volume constant, *a*	m^3/t	**32.7056**
Langmuir pressure constant, *b*	Pa^{-1}	**0.6562×10^{-6}**
Young's modulus of coal, E	Pa	**3000×10^6**
Poisson's ratio of coal,*v*		0.33
Moisture content of coal, M	%	0.56
Ash content of coal, A	**%**	**7.97**

3.2 BOUNDARY CONDITIONS AND INITIAL VALUES

1) Boundary conditions: Gas migration only occurs in coal seam. And the gas permeability for the roof and floor of coal seam is tiny. Therefore, they can be regarded as impermeable strata, namely zero flux impermeable boundaries. Thus the boundary conditions of the seepage field are expressed as follow:

$$\begin{cases} \dfrac{\partial p}{\partial x} = 0, x = \pm 20 \\ \dfrac{\partial p}{\partial y} = 0, y = \pm 3 \qquad t \in [0, \infty) \\ p(x, y, t) = p_0, x^2 + y^2 = r^2 \end{cases} \tag{8}$$

The displacement of the left and right boundaries and bottom boundary of model are restricted along the normal direction. The top boundary of coal seam burdens the weight of overburden stratum, and the upper part is free, meanwhile the weight of coal mass is also taken into account.

2) Initial conditions: There is a constant initial gas pressure of 1.2MPa for the model. Therefore, $p(x, y, 0)$ is equal to 1.2MPa. And the negative drainage pressure of borehole is 13kPa. Moreover, the initial displacement of stress field around the borehole is zero.

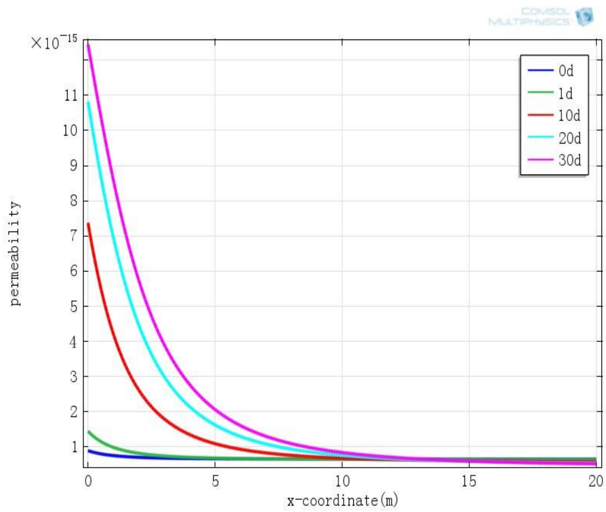


FIGURE 3 Variations of coal permeability with respect to different time

4 Calculation model

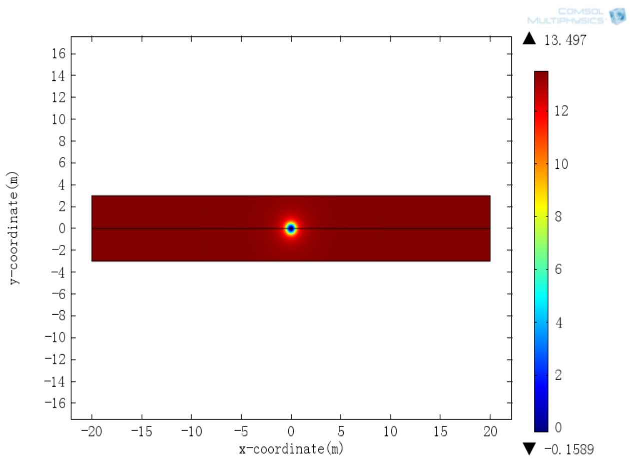
4.1 EVOLUTION OF PERMEABILITY

According the fluid-solid coupling model for coal mass around drainage borehole, the results are shown as the change curves of permeability for coal mass at different drainage time in Fig. 3.

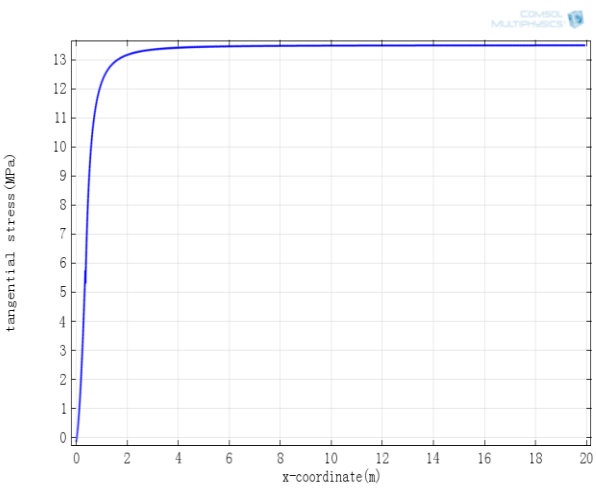
It is obviously observed from Fig.3 that, 1) The presence of borehole disturbs the balance state of stress for the surrounding coal mass of borehole, leading to the stress redistribution. With the increase of drainage time, the stress gradually removes into deep. And the pore and fracture in the coal mass are connected due to the stress concentration. The permeability increases from the initial one of $0.8\times10^{-15}m^2$ to $1.23\times10^{-14}m^2$ by 15.4 times after 30 days; 2) The permeability of coal mass around drainage borehole gradually decreases from the borehole wall to deep, and the decreased amplitude is in magnitude changes, that is to say the permeability of borehole wall is $0.8\times10^{-15}m^2$ at the beginning, and increases up to $0.2\times10^{-17}m^2$ in the deep, then gradually rebounds to the initial permeability.

4.2 ANALYSIS ON THE STRESS IN SURROUNDING COAL MASS OF BOREHOLE

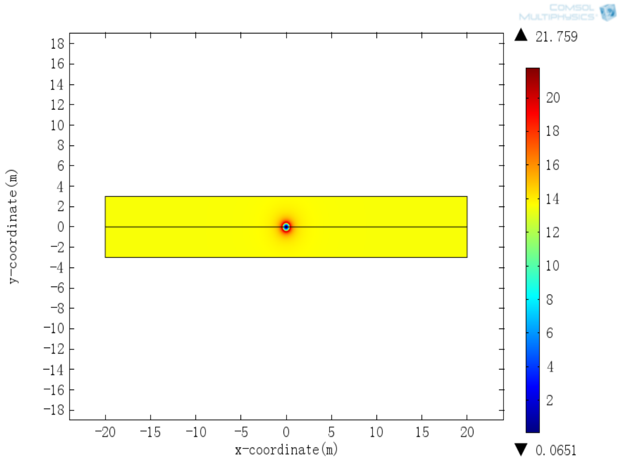
The actual conditions for the coal seams are taken into account in this simulation. While the burial depth of coal seam is 500m, the initial total stress about 13.5MPa is applied on the model. And the simulation results are shown in Figure 4



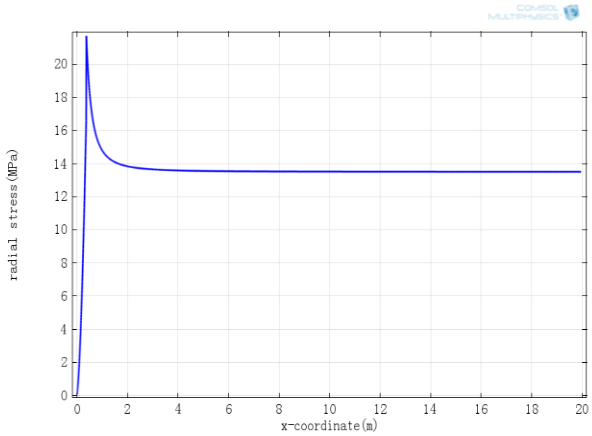
(a) Cloud map of radial stress



(b) Curve of radial stress



(c) Cloud map of tangential stress



(d) Curve of tangential stress

FIGURE 4 The stress distribution of coal mass around the borehole

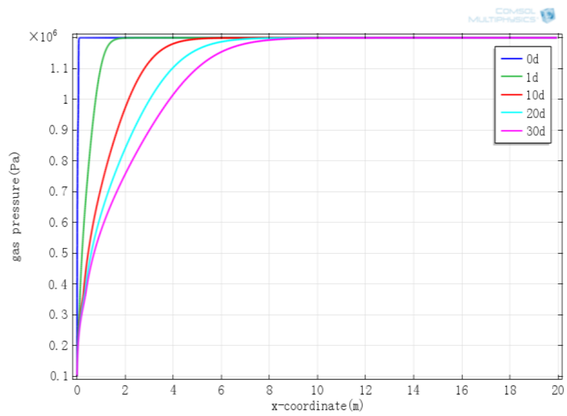
As illustrated in Figure 4, the tangential stress of coal mass around the borehole increases from 0MPa to 13.5MPa, transferring from the wall to the deep. And the tangential stress in the junction of elastic zone and plastic zone is up to the maximum value of 21.75MPa. Then the tangential stress gradually reduces to the initial state. These variations are in accordance with the evolution of permeability of coal mass around the borehole, which verifies the accuracy of the numerical model.

4.3 SIMULATION AND CALCULATION OF GAS DRAINAGE RADIUS

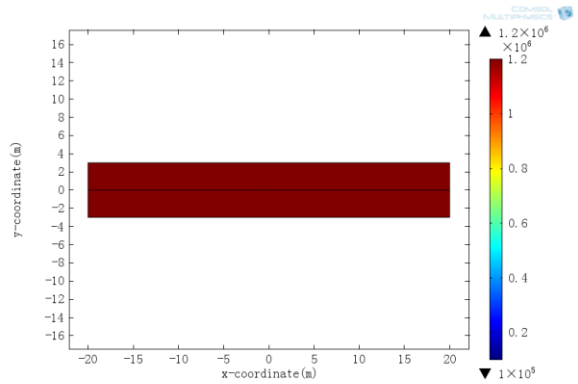
During the process of actual gas drainage, the effective drainage radius is determined for the spacing between boreholes. And the effective drainage radius of borehole has vital significance to apply the correct borehole drainage methods and design a reasonable arrangement of boreholes for the ideal drainage effects.

In order to obtain the effective drainage radius, the range of the zone where the gas pressure reduces lower than 0.74MPa is regarded as the gas drainage radius in this thesis. And the model is simulated by the PDEs model of simulation software. Before the simulation for the drainage radius, the parameters, such as the initial field stress of coal seams, the initial gas pressure, uniaxial compressive strength of coal, internal friction angle, Poisson's ratio, initial porosity of coal, permeability coefficient and so on, are determined firstly. And the distribution characters of gas pressure in the coal mass around the borehole are simulated while the drainage time is separately 0 day, 1 day, 10 days, 20 days and 30 days. The simulation results are shown in Fig.5. And Fig. 5 (a) implies the distribution curves for gas pressure of the coal mass around the borehole with respect to different drainage time while the negative drainage pressure is assigned to 13kPa. Fig.5(b~e) denote the cloud maps for gas pressure of the coal mass around the borehole.

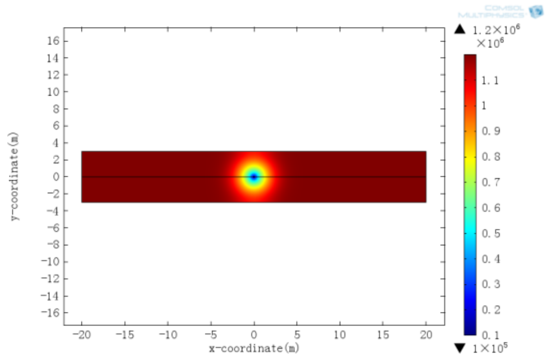
As shown in Figure 5 (a), the drainage radius increases continuously as time elapses, and the radius is respectively 0.33m, 0.92m and 1.31m when the time is 0 day, 10 days and 20 days, correspondingly. In this respect, these variations reflect the increase in coal permeability during gas drainage process.



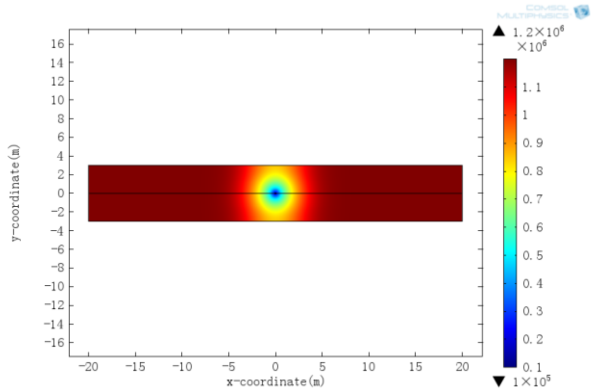
(a) Distribution of gas pressure in coal mass around borehole at different drainage times



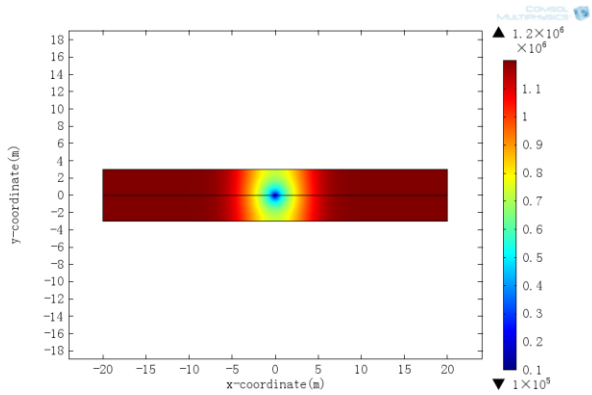
(b) Distribution of gas pressure at initial drainage time



(c) Distribution of gas pressure during drainage after 10 days



(d) Distribution of gas pressure during drainage after 20 days



(e) Distribution of gas pressure during drainage after 30 days

FIGURE 5 Distribution of gas pressure in coal mass around borehole at different drainage time

The drainage radius of borehole increases, so do the influence range of drainage negative pressure and the relief of stress in coal seams around the borehole as well as the gas permeability of coal seam in relief zone. But during the actual application process, due to the coal containing gas as the viscoelastic-plastic medium, the changes in the stress lead to the borehole deformation increasing with the time increasing, further resulting in the blockage of borehole. Therefore, the reasonable borehole spacing and drainage radius can be chosen according to Figure 5(a) for the engineering application. From the Figuer 5(b-e), it can be obviously seen that the drainage radius increases over time.

In the initial stage of gas drainage, gas pressure declines rapidly, so does the gas pressure gradient. With the increasing of drainage time, the gas pressure in coal mass containing gas reduces, implying that the gas drainage volume is very large in initial stage and turns to be stable after drainage. It is in accordance with the distribution of stress around the borehole in this calculation. As the stress concentration transfers from borehole wall to deep coal, the stress around the borehole redistributes. And the pore and fracture in the coal is compacted, thus the permeability decreases due to the increasing difficulty of drainage. So the gas pressure in the deep coal is not easy to reduce quickly, even presenting the original state. The distribution is consistent for the simulation results in references [18].

5 Conclusions

1) The fluid-solid coupling model of coal mass around borehole is deduced theoretically, and through the multi-physical field coupling software, the timeliness for permeability of coal mass around borehole at different time are analyzed. It is concluded that with the increase of drainage time, the concentrated stress of coal mass around the borehole gradually shifts to deep, so the internal pore and fissure of coal mass suffered stress concentration and then be connected. The permeability presents a gradually increasing trend, but from the borehole wall to the deep, the permeability gradually reduces, finally rebounds to the initial one. The stress distribution around the borehole is consistent with the evolution of permeability.

2) The gas pressure distribution of coal mass around borehole at different drainage time is analyzed. With the passage of time, the gas pressure reduces gradually, however the gas drainage radius increases correspondingly, the drainage rate slows down by steps.

3) Through the simulation of the dynamic drainage process for coal mass around the borehole, the two-dimensional model of excavation and extraction is simulated on the basis of the induced fluid-solid coupling model, and the stress distribution is close to the actual conditions, moreover, the gas pressure distribution of coal mass around the borehole and the evolution of coal permeability are obtained. The results are consistent with the general rule of local gas drainage.

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Authors

Bo Li, 1985.9, Jiaozuo City, Henan Province, P.R. China

Current position, grades: Lecturer of School of Safety Science and Technology, Henan Polytechnic University, P.R. China.
University studies: Graduated from China University of Mining and Technology (Beijing), China in 2013, received a doctor's degree in Safety Science and Engineering.
Scientific interest: Prediction and prevention of gas disasters, Dynamic disasters of coal and rock instability.
Publications: Presided over 3 scientific research projects the completion of provincial; more than 10 papers published in various journals.
Experience: Graduated from China University of Mining and Technology (Beijing), China in 2013, received a doctor's degree in Safety Science and Engineering, was approved as a tutor of graduate students in 2014; has completed 1 scientific research projects; more than 10 papers published in various journals.

Jianping Wei, 1971, Jiaozuo City, Henan Province, P.R. China

Current position, grades: Doctoral supervisor of School of Safety Science and Technology, Henan Polytechnic University, P.R. China.
Scientific interest: Prediction and prevention of gas disasters
Publications: Presided over 10 scientific research projects the completion of provincial; more than 50 papers published in various journals.

Peng Li, 1987,7, Beijing City, P.R. China

Current position, grades: Doctoral student of Faculty of Resource and Safety Engineering, China University of Mining & Technology, P.R. China.
Scientific interest: Prediction and prevention of gas disasters
Publications: 3 papers published in various journals.