A numerical method of hydraulic fracturing in coal seam for enhancing gas drainage

Abstract. Hydraulic fracturing technology, as one of the measures to enhance the coal seam permeability artificially and increase the coalbed-methane gas extraction rate, has its remarkable advantages. Although the interaction between fluid and coal has been studied comprehensively in the process of fracturing and gas drainage, fewer researchers focus on the combination of solid-gas-water three-phase flow, which brings great deviations to the design of hydraulic fracturing enhanced underground gas drainage. In this paper, a fracture-pore equivalent model is proposed, which establishes the equivalent relationship between the fracture aperture under hydraulic fracturing and the permeability coefficient of coal in the process of gas extraction, thus realizing the weak coupling between gas-solid-water. The hydraulic fracturing takes into account the deformation and fracture of solids driven by fluids. And the gas extraction considering simultaneously adsorption and desorption effect and the permeability coefficient caused by hydraulic fracturing is realized by the coupling of solid stress field and pore seepage field. The accuracy of this method is verified by comparing with the theoretical solution of the KGD model. Taking the fracturing boreholes in a mine's field test as the background, the change of the cracks distribution with the injection pressure is analysed quantitatively. And the relationship between gas extraction rate and time is verified by the field monitoring data. The results show that the model has positive significance for the optimal design of gas extraction scheme under hydraulic fracturing.

1. Introduction
As an important fossil energy resource, coal plays an irreplaceable role in the world economic development [1-4]. The coal seam gas reservoirs in China has the characteristics of micro-porosity, low permeability and high adsorption. Mining of high gas and low permeability coal seam is often accompanied by the occurrence of mine gas disasters, such as coal and gas outburst and gas explosion, resulting in a large number of casualties and property losses. Aiming at the difficulty of gas mining in low permeability coal seam, the development of hydraulic fracturing technology in domestic coal seam area gas treatment process has become increasingly mature, through the implementation of hydraulic fracturing measures, the coal seam gas permeability can be increased, improve the efficiency of gas extraction [5-8].

The research of gas extraction based on hydraulic fracturing mainly includes physical experiment method and numerical calculation method. From the perspective of physical experiment, Cai [9] designed a three-dimensional simulation experimental device for coal and gas outburst according to the similarity theory, and concluded that stress and mechanical properties of coal are the main factors that determine the strength of outburst. Sun et al. [10] conducted field tests on the anti-reflection technology of hydraulic fracturing, and the test results showed that drilling hydraulic fracturing can effectively improve the permeability of coal seam and the effect of drilling gas extraction. Pang [11] used hydraulic fracturing technology to carry out industrial tests in Baijiao Coal Mine, and analysed the mechanical mechanism of hydraulic fracturing of coal body. The results show that hydraulic fracturing can increase the pure amount of gas extraction by about 7 times. Zhou et al. [12] analysed the mechanism of fracturing and anti-reflection, fracturing radius and extraction effect of hydraulic fracturing coal body, etc. The field application results showed that hydraulic fracturing increased the
permeability of coal seam by 67 times, and the extraction concentration and purity of gas by more than 4 times. From the perspective of numerical calculation, Chen et al. [13] studied the mechanism of seepage-stress coupling effect of gas-water two-phase flow by establishing a permeability evolution model of multi-fractured media and considering the process of gas adsorption and desorption. Yin et al. [14] established a solid-gas coupling model that can describe the framework deformability and gas compressibility in the case of gas-solid coupling of coal rock containing gas by introducing the expansion stress generated by gas adsorption in porous media. Zhao et al. [15] established the mathematical model of gas flow in homogeneous coal seam under solid-gas coupling. Wang et al. [16] based on Continuum-Discontinuum Element Method (CDEM) and central Finite Volume Method (Finite Volume Method, FVM), a two-dimensional hybrid numerical model is proposed to solve the fluid-structure coupling problem in hydraulic fracturing. Hu et al. [17] used finite element software to simulate the hydraulic fracturing process of high gas and low permeability coal seams, and the results showed that the anti-permeability technology of hydraulic fracturing was helpful to increase the permeability of low permeability coal seams, and the numerical simulation was less different from the actual situation. Jin et al. [18] used FLAC3D to carry out the numerical simulation of coal seam hydraulic fracturing, and obtained the law of crack propagation in the process of coal seam hydraulic fracturing. In this work, we extend previous models and propose a three-phase weakly coupled gas-solid - water model to realize the simulation of the whole process of gas extraction under hydraulic fracturing. This model includes two stages: hydraulic fracturing and gas drainage. In hydraulic fracturing stage, based on CDEM model, the non-uniform distribution characteristics of fractures driven by fluid can be described. And in gas drainage stage, the gas extraction simulation under hydraulic fracturing can be realized by converting the aperture of fracture element to the permeability coefficient of pore element.

2. Modelling

2.1. Governing equation of hydraulic fracturing
Hydraulic fracturing is a dynamic coupling process between the flow of fracturing fluid in fractures and the deformation of coal and rock mass. In this paper, the solid stress field and crack growth are solved by CDEM method [19-21]. For each finite element in the spatial domain, the governing equation can be expressed as

\[
M \dddot{u} + C \dot{\ddot{u}} + K u = F^e
\]

where \( M \) represents the concentrated mass matrix, \( C \) represents the damping matrix, \( K \) represents the element stiffness matrix, \( \dot{u} \) represents the element displacement array, and \( F^e \) represents the element external force array, including the force and fluid pressure. The coupling between the fracture seepage field and the solid deformation calculation adopts the method in reference [22]. In this method, the fracture element is located on the contact surface between the solid elements, and the fracture seepage obeys the cubic law:

\[
k = \frac{w^2}{12\mu}
\]

where \( k \) is the fracture permeability coefficient, \( \mu \) is the dynamic viscosity of fluid, and \( w \) is the fracture aperture.

2.2. Governing equation of gas drainage
The equilibrium equation of coal-rock mass can be expressed by the following formula:

\[
\sigma_{g,i,j} + F_i = 0, \quad i = 1, 2, 3
\]

where, \( \sigma_{g,i,j} \) represents solid stress component, \( F_i \) is the volume force in the \( i \)th component. When gas seepage is coupled with solid calculation, the volume deformation of solid will have an impact on the porosity of coal seam. The formula is as follows
where, \( n' \) is the current porosity of node, \( n_0 \) is the initial porosity of node, and \( \theta \) is the element volumetric strain.

2.3. Equivalent relationship between permeability and crack aperture

2.3.1. Equivalent method.

The schematic diagram of pore and fissure units is shown in Figure 1, which contains 3 pore elements and 9 fracture elements, and the fracture elements are located at the junction of adjacent pore elements.

\[
K_{eq} = K_0 + \frac{w_{eq} - w_0}{w_{max} - w_0} (K_{max} - K_0)
\]

where \( w_0 \) represents the initial fracture aperture, \( w_{max} \) represents the maximum fracture aperture, \( K_0 \) represents the pore permeability coefficient corresponding to the initial fracture aperture, \( K_{max} \) represents the pore permeability coefficient corresponding to the maximum fracture aperture, and \( w_{eq} \) represents the equivalent fracture aperture.

\[
w_{eq} = \frac{1}{n} \sum_{j=1}^{n} w_j
\]

where \( w_j \) represents the aperture of the fracture element adjacent to the pore element.

3. Compared with KGD analytical solution

KGD analytical solution is often used to analyse the crack growth process in hydraulic fracturing simulation. In order to verify the accuracy of the coupling calculation program between the fracture seepage field and the solid stress field, a 200m×200m numerical model was established (as shown in Figure 2). The model contains two kinds of meshes, the solid mesh and the fracture mesh. The solid mesh is discretized by 8,616 triangular elements, that is, contact surfaces are created at adjacent triangular element boundaries to provide potential crack channels for solid failure. The fracture mesh is inherited from the solid mesh, that is, it is created at the contact surface of the solid mesh.
In the calculation of solid stress field and fracture seepage field, normal constraints are applied around the model. A single crack is pre-set at Y=100m, and fluid is injected at the coordinate (0,100) with a flow rate of 1L/s/m. The calculation parameters of the model are shown in Table 1. In order to compare the calculation results of the KGD theoretical model, the solid strength is ignored, that is, it is assumed that the solid fracture occurs when the fluid arrives.

Table 1. Parameters for simulation of KGD model.

| Media  | Parameter                  | Symbol | Value |
|--------|----------------------------|--------|-------|
| Rock   | Young’s modulus           | \( E \) (GPa) | 19.9  |
|        | Poisson’s ratio            | \( \nu \) | 0.2   |
|        | Density                    | \( \rho \) (kg.m\(^{-3}\)) | 2500  |
| Fluid  | Dynamic viscosity          | \( \mu \) (mPa.s) | 1.0   |
|        | Initial fracture width     | \( w_0 \) (m) | 2e-5  |
|        | Density                    | \( \rho \) (kg.m\(^{-3}\)) | 1000  |

Crack propagation at \( t = 350s \) is shown in Figure 3 (displacement amplify 2000 times). The change of fracture aperture(\( w_0 \)) at the injection point with time is shown in Figure 4, and the change of unilateral crack length (\( L \)) with time is shown in Figure 5.

The numerical solution of fracture aperture at injection point in Figure 4 is larger than the theoretical solution in the middle stage of calculation, and it is in better agreement with the theoretical solution in the beginning and late stage. Figure 5 shows the variation trend of unilateral crack length with time, which is smaller than the theoretical solution in the middle stage of calculation, and basically consistent with the theoretical solution in the early and late stage of calculation. In general, the numerical and theoretical solutions are basically consistent, which verifies the correctness of the numerical method presented in this paper.

Figure 4. Comparison between numerical and analytical results in terms of fracture width at wellbore.

Figure 5. Comparison between numerical and analytical results in terms of half fracture length.

4. Application in field

4.1. Numerical model and solving conditions

In this paper, the 3002-working face of Hemei Coal Mine is taken as the research object, and the numerical model is established, as shown in Figure 6. The model is 20m in length and 7m in height, which only includes coal seam. The injection hole is located at the middle of the coal seam, with coordinate (7.5, 3.5), and the coordinates of control holes are (2.5, 3.5) and (12.5, 3.5) respectively. In the calculation of solid stress field, considering the buried depth of the coal seam is about 600m, the top side is set as the load boundaries with stresses of 15 MPa, the bottom of the model is fixed, and the left and right side are set as the roller boundary, which confines the normal displacement. In the
calculation of seepage field, the point source flow rate of each inject hole is $1.4 \times 10^{-3} \text{ m}^3\text{s}^{-1}$ and continued to be injected for 1h.

![Figure 6. Computational Model of Hemei coal mine.](image)

The calculation process of this model is divided into two calculation processes, hydraulic fracturing and gas drainage. Hydraulic fracturing for obtaining the fracture aperture is the coupling calculation of fracture seepage and solid stress filed. Gas drainage is calculated as pore seepage, and the fracture opening obtained in hydraulic fracturing is equivalent to the permeability coefficient of pore elements, so as to achieve the purpose of anti-reflection in fracturing. Some mechanical parameters of coal and rock mass used in calculation are shown in Table 2, and seepage parameters are shown in Table 3.

### Table 2. Simulation parameters of solids.

| Media | $\rho/(\text{kg.m}^{-3})$ | $E/$GPa | $\nu$ | $T/$MPa | $\phi/(^\circ)$ |
|-------|--------------------------|---------|-------|---------|----------------|
| Coal  | 1400                     | 0.50    | 0.32  | 0.20    | 15             |

### Table 3. Simulation parameters of seepage.

| Type            | Parameter         | Symbol       | Value  |
|-----------------|-------------------|--------------|--------|
| Fracture seepage| Initial fracture width | $w_0$/m       | 1.0e-5 |
|                 | Bulk modulus      | $K_f$/MPa    | 10     |
|                 | Flow rate         | $q_0/(\text{m}^3\text{s}^{-1})$ | 1.4e-3 |
|                 | Dynamic viscosity | $\mu$/mPa.s  | 1.0    |
| Pore seepage    | Density           | $\rho/(\text{kg.m}^{-3})$ | 0.716  |
|                 | Porosity          | $f_0$        | 0.01   |

4.2. Results and analyses

4.2.1. Hydraulic fracturing

In the calculation stage of hydraulic fracturing, the initial fracture opening is shown in Table 1. In this paper, it is assumed that the maximum fracture opening $W_{\text{max}} = 5.0 \times 10^{-5}$ m. According to the provisions of the Code for Geological Investigation of Water Conservancy and Hydropower Engineering (GB50287-99) [23], The permeability coefficients corresponding to the initial crack opening $w_0$ and the maximum crack opening $w_{\text{max}}$ are respectively $K_0 = 1.0 \times 10^{-11} \text{ m}^2/\text{Pa/s}$ and $K_{\text{max}} = 1.0 \times 10^{-10} \text{ m}^2/\text{Pa/s}$.

The time history curves of fracture aperture and fracture pressure are shown in Figure 7. At the initial stage of fracturing ($<15$s), the fracture pressure rises sharply to 13.8MPa while the water injection
flow remains unchanged. During 15s~1.75min, because the pressure in the fracture is not enough to make the fracture grow, the fracture aperture remains unchanged, and the pressure in the fracture fluctuates dynamically. When the pressure in the fracture rises to the tensile strength of the coal body, the crack begins to grow. In this stage (1.75min~3.3min), the fracture aperture increases linearly, and the fracture pressure decreases slightly due to the flow of fluid from the fracture. After that (> 3.3min), the fracture pressure gradually increased and finally fluctuated dynamically at about 12MPa, and the fracture aperture remained basically unchanged. The pressure fluctuation process of the injection holes reflects the crack propagation process to a certain extent. The relationship curve between the fracture aperture and the pore permeability coefficient is shown in Figure 8. The larger the fracture aperture is, the larger the pore permeability coefficient is, and there is basically a linear change between the two, indicating the correctness of Equation 5.

Figure 7. The time history curve of the fracture aperture and fracture pressure coefficient.

Figure 8. The curve of relation between pore permeability and fracture width.

The fluid boundary condition of injection hole is changed from flow boundary to pressure boundary. The cracks distribution under different water injection pressures (16MPa, 18MPa, 20MPa) are obtained (Figure 9a-9c). It can be seen from the figures that cracks are mainly developed horizontally and develop more fully with the increase of water injection pressure. According to the definition of crack ratio in reference [24], the curve of crack ratio in the three cases is obtained, as shown in Figure 9(d).

(a)16MPa  (b)18MPa  (c)20MPa  (d)The curve of crack ratio

Figure 9. Cracks distribution under different fluid injection pressures
4.2.2. Gas drainage

The variation curve of cumulative gas emission over time is shown in Figure 10. In the initial stage of gas extraction, the gas emission continues to increase with time, and the final emission tends to be stable with time growth, which is basically consistent with the experimental phenomenon conducted by Duan et al. [25].

The curve of real-time gas drainage over time is shown in Figure 11. According to the numerical results, it can be found that in the early stage of gas extraction, the gas drainage velocity gradually increases to the peak value with the increase of time, then decreases, and finally tends to be stable. It can be found from the on-site real-time monitoring results that the gas drainage velocity at the initial stage gradually increases to a small wave peak with the increase of time, and then decreases gradually, and then increases again to a peak with the increase of time, and finally decreases gradually and tends to be stable. Compared with the numerical calculation results, the field monitoring results showed a small wave peak before reaching the maximum peak. Considering the complexity and uncertainty of various factors in field tests, it can be concluded that the numerical calculation results are basically consistent with the variation trend of field monitoring results.

![Figure 10](image1.jpg)  
*Figure 10. The time history curve of the cumulative gas drainage.*

![Figure 11](image2.jpg)  
*Figure 11. The time history curve of the real-time gas drainage.*

5. Conclusions

Based on the water-solid coupling model and gas-solid coupling model, a fracture-pore equivalent model is proposed in this paper, which establishes the equivalent relationship between the fracture aperture under hydraulic fracturing and the permeability coefficient of coal in the process of gas extraction, thus realizing the weak coupling between gas-solid and water. In hydraulic fracturing calculation, when the pressure in the fracture is less than the tensile strength of the coal body, the fracture aperture remains unchanged, the fluid pressure rises, and the fluid flows out rapidly after the cracks expand, leading to the decrease in pressure. The pore permeability coefficient increases with the increase of the fracture aperture, and the two change linearly, indicating that hydraulic fracturing can increase the fracture opening and improve the permeability of coal mass. The cumulative gas drainage context gradually increases with the increase of time and finally tends to be stable. The transformation of gas extraction rate with time shows a phenomenon that increases first, then decreases and finally tends to be stable, which is basically consistent with the field monitoring results.

6. References

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