The propagation research of hydraulically created fractures in coal seams based on discrete element method

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Abstract. Coalbed methane (CBM) is clean unconventional energy that can be exploited with stimulation treatment to realize commercial value, and hydraulic fracturing is the key technology for increasing CBM production. The simulation of hydraulic fractures is an important research content that can guide the engineering practice to achieve the purpose of increasing production. Based on the distribution characteristic of cleats in coal, the research on the propagation of hydraulic fractures is carried out via Discrete element method (DEM). The simulated results show that: hydraulic fractures mainly propagate along the cleats towards the maximum principal stress. The fracture network can be formed due to the intersection of face cleats and butt cleats that can propagate at certain pressure. During the injection process of fracturing fluid, the pressure at injection point decreases with the fracture propagation until the pressure tends to be stable. With the increase of injection rate and fracturing fluid viscosity at the same condition, the maximum aperture of hydraulic fracture increases, while the length of principal hydraulic fracture shortens. Therefore, to achieve the purpose of forming hydraulic fracture network in coal seams with cleats, low viscosity fracturing fluid and low injection rate need be applied to the fracturing technology. As the cleat density increases, the number of branch fractures increases, but the length of principal hydraulic fracture becomes short. Long and narrow hydraulic fractures are easily formed in coal seams with lower cleat density.

1. Introduction

Hydraulic fracturing is a necessary stimulation for CBM industrial exploitation [1]. Artificial fractures induced by fracturing can effectively connect the wellbore with the reservoir, which can promote desorption and diffusion of CBM and increase the CBM production [2].

Geological parameters, fracturing fluid properties and construction parameters can have impact on the morphology of artificial fractures. Laboratory study on true triaxial fracturing of coal and fracture
monitoring at the site show that hydraulic fractures in coal seams mainly initiate and propagate along the cleats, and complex and irregular multi-fractures are asymmetric distribution [3-6]. Hydraulic fractures in coal seams mainly propagate along the cleats, and fracture morphology is mostly asymmetric and irregular. Therefore, the applications of conventional two-dimensional and three-dimensional fracture models are restricted in most of coal seams [7]. To solve the problem of fracture propagation in the fractured reservoirs such as coal seams, a lot of work have been carried out in the numerical simulation.

At present, discrete model of fracture network [8, 9], wire-mesh model [10, 11], unconventional fracture model [12] and finite element model [13] can be applied in the fractured reservoirs. However, discrete element method (DEM) has a unique advantage in dealing with the fracture propagation of discontinuous medium. Zhao et al. [14] simulated the interaction between hydraulic fractures and natural fractures via two-dimensional particle DEM. Zangeneh et al. [15] applied two-dimensional DEM (UDEC software) to the simulation of hydraulic fracture propagation. In the simulation, the rock was divided by definitive cleats, and the block between cleats can have deformation. Nagel et al. [16] researched the law of fracture initiation and propagation and their influence factors in the fractured reservoirs with three-dimensional DEM. Hamidi et al. [17] developed and simulated fracture initiation and propagation in the fracturing process based on three-dimensional DEM. Damjanac [18] initially realized a fully coupled three-dimensional numerical model of fluid flow in the deformation fractured rock with three-dimensional discrete element code (3DEC). Savitski researched the response of fractured rock to fluid injection and hydraulic fracturing via 3DEC software [19]. Zhang et al. [20] analyzed the influence of natural fractures on hydraulic fracturing by means of adding discrete fracture networks (DFN) to the 3DEC model. Damjanac [21] simulated hydraulic fracturing in the discrete element software and analyzed the influence of DFN on fracture propagation.

The previous results show that complex fractures can be formed mainly due to the interference of natural fractures in the process of hydraulic fracturing, so the key of different simulated methods reveals the interaction of different fractures. The existing numerical simulations of fractures are mainly aimed at shale and tight sandstone, while the relevant simulated research on fracture propagation is less in the field of coal. Coal has approximately orthogonal distribution of face cleats and butt cleats that are not possessed in the other fractured reservoirs. DEM has a great advantage in dealing with the problems on discontinuous structural mechanics of natural fractured reservoirs [22]. In this paper, the propagation laws of hydraulic fractures in coal seams are studied based on DEM, which can guide the engineering practice of fracturing in coal seams.

2. The simulated principal of 3DEC

DEM firstly proposed by Cundall [23] in 1971 is a numerical simulated method to specially solve the problem of discontinuous medium. This method considers the rock composed of discrete blocks and cleats. Blocks can shift, rotate and deform, while cleats can be compressed, separated and slid. Therefore, the rock can be considered as the discontinuous and discrete medium that more actually reflect the nonlinear deformation characteristics of the rock with cleats. In addition, this method can express any complicated constitutive relation as tiny increments in the calculation, and no solution equations do not exist [24]. The program of 3DEC was developed by Cundall and ITASCA consulting group in 1986. The FISH language embedded in the 3DEC program can make users define new variables and functions, which can extend the computing program and add user-defined characteristics.

Flow-solid mechanics can be coupled with DEM in the simulated fracturing. Fracturing fluid can flow in the cleats of rock, while the rock itself is assumed to be impermeable. Each contact point is given a hydraulic aperture \( u_h \), and its relationship with the normal displacement \( \Delta u_n \) of contact point can be shown as:

\[
u_h = u_0 + \Delta u_n\]

Such that \( u_0 \) is the hydraulic aperture when the normal stress is 0, and the normal displacement of cleat is positive. It is assumed that the minimum residual value of cleat aperture is \( u_{res} \) at greater
confining stress. Water flow in the cleats can be considered as the laminar flow of viscous fluid between parallel plates. The fluid flow rate conforms to the cubic law, which means that the fluid flow rate is directly proportional to the cubic value of cleat aperture:

$$q_i = -\frac{u_0^3 \rho g \phi}{12 \mu}$$  \hspace{1cm} (2)

Such that $q_i$ is the fluid flow rate; $u_0(x_i)$ is the hydraulic aperture at some point $x_i$ ($i=1, 2…$) in the plane; $\phi = z + p/\rho g$ is the hydraulic head; $g$ is the acceleration due to gravity; $\rho$ is the fluid density; $\mu$ is the fluid viscosity; $z$ is the elevation; and $p$ is the pressure in the fluid.

The pore pressure changes with the variation of cleat aperture, so new pore pressure can be shown as:

$$P = P_0 + K_w Q \frac{V}{V} - K_m \frac{V - V_0}{V}$$  \hspace{1cm} (3)

Such that $P_0$ is the pore pressure at previous time step; $Q$ is the sum of fluid flow rate from all contact points around the pore; $K_w$ is the volume modulus of fluid; $V$ and $V_0$ are, respective, the pore volume at present time step and previous time step, and the relationship is as follows:

$$\Delta V = V - V_0, \quad V_m = \frac{V + V_0}{2}$$  \hspace{1cm} (4)

Pore pressure, contact force at contact points of block and external load are combined to participate in the calculation cycle on the block. In this way, the stress inside the block is the complete stress, while the normal stress at contact point is the effective stress.

3. The selected parameters of fracturing simulation

True triaxial fracturing experiment is a method of fracturing research that can be used to understand the mechanism of fracture initiation and propagation, and then experimental results can guide engineering practice of fracturing. However, true triaxial fracturing experiment has the problem of high cost and difficult sampling, so its widespread application is restricted. Moreover, the physical experiment cannot observe the dynamic variation of hydraulic fractures during the propagation, and the fracture morphology can be only observed with eyes or scanning technique. To solve the problem, the propagation law of fractures is often studied by numerical simulation instead of physical experiment. In the paper, reservoir model with the size of 200×200×40 m is established by the software of 3DEC, and based on the model, face cleats and butt cleats are introduced with the help of DFN model. The thickness of coal seam is set to 10m, and fracturing injection is located in the middle of reservoir model. Dip angle of the cleat is 90°, and face cleat is perpendicular to butt cleat. In addition, eleven monitoring points are set in the model for observing pressure variation in the fracturing process. Fracturing model is shown in Figure 1, and parameters of the model are listed in Table 1.
### Table 1. Simulated parameters

| Type                          | Parameter                  | Value |
|-------------------------------|----------------------------|-------|
| Petrologic parameters         | Density (g/cm$^3$)         | 1.5   |
|                               | Cohesion (MPa)             | 7.04  |
|                               | Internal friction angle (°)| 22.43 |
|                               | Tensile strength (MPa)     | 1.9   |
|                               | Young’s modulus (GPa)      | 4     |
|                               | Poisson’s ratio            | 0.3   |
|                               | Normal stiffness (GPa/m)    | 7.42  |
|                               | Shear stiffness (GPa/m)     | 1.46  |
|                               | Residual hydraulic aperture (μm) | 1 |
|                               | Aperture at zero stress (μm) | 10 |
|                               | Maximum hydraulic aperture (μm) | 1000 |
| Parameters of CBM well        | Well depth (m)             | 856   |
|                               | Vertical stress (MPa)       | 21.8  |
|                               | Maximum horizontal principal stress (MPa) | 22.6 |
|                               | Minimum horizontal principal stress | 18.9 |
| Fluid parameters              | Injection rate (m$^3$/min) | 6     |
|                               | Fracturing fluid viscosity (mPa·s) | 1 |

a. Pressure distribution in the hydraulic fractures

b. The distribution of hydraulic fracture aperture

**Figure 2.** The distribution of principal fracture pressure and aperture in the reservoir model
Simulated results show that hydraulic fracture initiates along the cleat, and initial pressure drops immediately after reaching the peak. Then, as the fracture propagates, propagation pressures at the monitoring points increase successively, and pressures are getting closer each other with the increase of injection time (Figure 2a). The principal fracture propagates asymmetrically along the maximum horizontal principal stress, and the fracture aperture is also non-uniform. When the principal fracture encounters cleats in the process of propagation, branch fractures are formed owing to cleats opening, but branch fractures cannot always propagate as a result of the difference between horizontal principal stresses (Figure 2b).

Fracture morphology is affected by construction parameters and geological conditions, therefore, to further analyze hydraulic fracture propagation, simulations are run at different injection rate, fracturing fluid viscosity and cleat density.

4. The analysis of influence factors

4.1 Injection rate

Injection rate as an important parameter for fracturing operation can have impact on proppant carrying capacity of fracturing fluid, fracture height control, leak-off loss and so on.

4.2 Fracturing fluid viscosity

Fracturing fluid viscosity is a key parameter for controlling fracture height and carrying proppant. Simulated results at different viscosity of fracturing fluid (1mPa·s, 10mPa·s and 50mPa·s) are shown in Figure 4.

With the increase of fracturing fluid viscosity, initial pressure increases, and when fracturing fluid viscosity is 50mPa·s, initial pressure is higher than propagation pressure. Higher viscosity can make principal fracture widen and shorten. In addition, as the viscosity increase, propagation pressure also
increases, while the propagation rate of principal fracture decreases by observing the pressure at different monitoring point. High viscosity goes against the formation of branch fractures.

![Simulated results at different viscosity of fracturing fluid](image)

Figure 4. Simulated results at different viscosity of fracturing fluid

4.3. Cleat density

Cleats are natural fractures formed in the process of coalification, which are divided into face cleats and butt cleats. Cleat density is an important parameter to characterize the number of cleats in coal seams. In the paper, DFN is used to simulate the cleats of coal, and volume density that expresses cleat area per unit coal volume is instead of cleat density. Simulated results at different cleat densities (0.04/0.08, 0.08/0.16 and 0.12/0.24) are shown in Figure 5.

![Simulated results at different cleat densities](image)

Figure 5. Simulated results at different cleat densities
The principal hydraulic fracture generally propagates along the maximum horizontal principal stress, but when it encounters cleats, branch fractures are formed, and asymmetric propagation will be carried out. With the cleat density increasing, the number of branch fractures increases, but the speed of pressure propagation decreases along the principal fracture, and due to the difference between horizontal principal stresses, the propagated length of branch fractures is shorter. As the cleat density increases, the length of principal hydraulic fracture decreases at the same injection rate and time, while the fracture aperture increases.

5. Conclusion
(1) Hydraulic fracture propagates along the maximum horizontal principal stress, but the propagation of principal fracture will be restrained owing to the influence of cleats. When principal fracture encounters cleats, the branch fractures will be formed, but the difference between horizontal principal stresses can affect the propagated length of branch fractures. The cleat can well initiate and propagate is in the position with a smaller angle to the maximum principal stress. The distribution of cleats is non-uniform in coal seams, so the propagation of hydraulic fractures is also asymmetric.

(2) Injection rate and fracturing fluid viscosity can influence the propagation of hydraulic fractures. With the increase of injection rate, initial pressure and propagation pressure increase. High injection rate can promote the propagation of fracture and the formation of wide aperture. Higher viscosity makes principal fracture widen and shorten and goes against the formation of branch fractures.

(3) The formation of branch fractures is affected by the cleat density. At the same condition, the greater the cleat density, the more the number of branch fractures. The growth of branch fractures can make the aperture of principal fracture increase, but its propagated length will shorten.

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