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ORIGINAL PAPER

NUMERICAL SIMULATING AND BENCHMARKING OF WATERJET FRACTURING PARAMETERS IN COAL BEDS

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ABSTRACT

Coal seam fracture stimulation practices indicated that the efficiency of methane drainage is improved initially but reduces thereafter. It is speculated that the contrasts of gas drainage efficiency before and after fracture stimulation may reflect variation of the closure behavior of the fracture created artificially. The work presented herein uses numerical modeling to study the effect of waterjet slotting parameters on the closure behavior of artificial fractures in coal seam. The modeling results indicated that the increase in the methane drainage efficiency due to the fracturing treatment depends upon the closure and residual behavior of fractures, which incorporates with the length, width and distribution of the fractures along the length of borehole and these controllable slotting parameters are directly linked to the fracture conductivity and, therefore, represent the main outcome of fracture stimulations, and significantly affect the success of the stimulation procedures used for the coalbed methane drainage.

1. INTRODUCTION

China is the biggest coal producer in the world, and is also the world's largest coal consumer, with coal accounting for approximately 70 % of China's total energy consumption. The geological structure of Chinese coal mines is very complicated; huge amounts of methane often burst from coal seams, and many coal mines are very gassy. Although gas drainage efficiency in China has been increased from 15 % in 1998 to 26 % in 2004, much of the captured gas is poor in quality. It is estimated that 70-80 % of drainage gas has a methane concentration of less than 30 % (Su et al., 2005). On the other hand, due to large coal consumption, the mining depth has significantly increased up to 800 – 1500 m (Wang et al., 2012), which results in high gas content and high gas pressure of the coal seam.

As a result, presence of explosive gases, predominantly methane, in coalbeds has always been a major problem in underground coal mining. Large amounts of methane formed during the coalification process and stored in coal seams are released in the mine workings gradually as mining progresses. Since methane in mines can cause a variety of problems ranging from asphyxiation and burning to violent explosions (Harpalani and Chen, 1995), so, the maximum allowable concentration of methane in the atmosphere in Chinese coal mines is 1 vol %.

Traditional method for coal seam degasification is to drill the borehole into the coal seam, then conduct gas drainage. With a continual increasing of mining depth, the coal seam permeability is reduced significantly. Therefore, to satisfy the safety requirements and regulations, artificial fractures created by the various fracturing techniques, such as, explosive fracture method, hydraulic fracture method, etc., are expected to act as gas exchangers to enhance the gas production before mining.

Recently, the highly pressurized waterjet technique has become the most common fracture stimulation technology for improving coal seam permeability and enhancing the efficiency of gas drainage in Chinese coal mining industry. The technique is developed for creating artificial fractures along the length of gas drainage borehole to increase coal seam permeability.

2. THE ISSUES RELATED TO ARTIFICIAL FRACTURING IN COAL SEAM

Coal is a porous structure of rocks and is formed with matrix pores and fractures, which determine migration and production of coal bed methane. Fractures of coal are divided into endogenous, exogenous and inheritance fractures. Endogenous and exogenous fractures are the result of coalification, constitution, stress, and inheritance fractures are transitional fractures. Fractures play a decisive role in gas migration, mobility and outputs.

Stimulating low and ultralow permeability coal seam for mining safety and gas utilization faces more technical challenges, but a number of techniques, as mentioned above have been developed and used in

Chinese coal mining industry. The mechanisms of these techniques are to create artificial fractures in the coal seam, provide a path for gas to be transported into the gas drainage system of the mine. Ultimately, these techniques lead to reduction of the occurrence of coal and gas outbursts during mining activities.

On the other hand, the field applications indicate that ground stress will make those multiple artificial fractures created artificially close again. The fracture tends to close because of the effect of minimum horizontal stress. Theoritically, the fracture closure is controlled by elastic, plastic, and viscous rock properties (Bybee, 2007) and it causes reduction in coal seam permeability, and significantly influences the efficiency of gas drainage.

Also, the geometry of artificial fractures in a coal seam are sensitive to changes in the pressure, time, and technical parameters selected, such as fracture width, length, etc. But how these parameters may influence the closure of artificial fractures in the coal seam is still poorly understood. Therefore, the major goal of this research is to contribute to the resolution of this issue, and enable an estimate of gas drainage effectiveness, which is essential for selecting the fracture stimulation parameters associated with the coal seams.

3. CLOSURE BEHAVIOR OF FRACTURE WIDTH

Permeability values for the coal matrix are typically eight orders of magnitude smaller than the fracture permeability value (Robertson, 2005). Therefore, most researchers generally ignore the coal – matrix permeability and attribute coal permeability directly to fracture permeability.

Fracture permeability may be related to fracture aperture through the cubic law (Jaeger et al., 2007), while fracture aperture is strongly dependent on the normal stress. Therefore, in this study, the closure of the fracture width will be studied in association with the waterjet slotting parameters and stress conditions.

4. RELATION BETWEEN PERMEABILITY AND OPEN SPACE OF COAL SEAM

Coal is a heterogeneous medium with dual pore systems including the matrix pores and natural fractures. It can be divided into two parts: the coal matrix and the natural fracture network. In the coal matrix, well developed micro-pores provide an adsorptive space for coalbed gasses. The natural fracture network is the dominant pathway of free fluids, consisting of exogenous (mainly caused by tectonic stress) and endogenous (including face and butt cleats formed by coalification) fractures and some interconnected macro-pores (Li, 2012). Coal seam permeability is a key parameter for gas drainage in the underground coal mine, which is mainly related to the open spaces in the coal seam. The theoretical relations between permeability and open space of the coal seam have been developed as follows.

4.1. FRACTURE PERMEABILITY

Fracture permeability, k, is defined as a piecewise constant value along the fracture centerline. At any given location, we compute permeability from the local aperture using the parallel plate law.

The parallel plate model for a single fracture can be extended to multiple fracture systems. The permeability through a set of parallel fractures of equal aperture, oriented parallel to flow direction, is given by (Zhang et al., 2007):

$$k = \frac{\boldsymbol{b}^3}{12\boldsymbol{s}} \tag{1}$$

Where, *s* is the mean fracture spacing between parallel fractures.

4.2. OTHER RESEARCH ON THE RELATIONSHIP BETWEEN PERMEABILITY AND FRACTURES

According to Wang et al. (2011), the permeability changes little with the presence of a radial fractures across the sample. However, the permeability increases by three orders of magnitude with a longitudinal fracture through the sample. This significant difference in permeability characterizes the nature of a coal seam composed of a matrix and cleat system in situ. This confirms that a typical coal seam, at the scale of meters, is a dual porosity dual permeability system.

Liu and Rutqvist's (2010) research indicated that the fracture permeability may be related to fracture aperture through the cubic law (Jaeger et al., 2007), while fracture aperture is a function of normal stress.

The previous work presented above explicitly indicates that the permeability range of a coal seam is primarily determined by the geometry of the fracture. Therefore, variation of the fracture geometry of coal is an important parameter affecting gas drainage of the coal seam.

Also, the mechanical properties of a coal seam, such as coal strength, may influence the characteristics of fracture closures. Thus, the modeling conducted in this work is carried out with the hard and soft coal seams respectively.

5. ASSUMPTIONS FOR THIS STUDY

Natural fractures within a coal seam are very complicated and dominate the efficiency of coal seam gas drainage before formation of the artificial fractures. In order to study the closure characteristics of artificial fractures in a coal seam, it is considered that the artificial fractures created by water jet fracturing technique is the only factor influencing the variation of gas emission of the coal seam before and after the fracture stimulation operation and the effect of natural fractures on gas drainage is not taken into consideration during this study on the basis of following assumptions as:

1. The contribution to gas emission of any natural fractures in a coal seam is kept unchanged before and after the formation of artificial fractures. It can be argued that the natural fractures in the coal seam will have some changes due to the variation of stress environment induced by the formation of artificial fractures, but comparing the contribution of gas drainage efficiency changes due to artificial fracture, the changes in gas drainage due to natural fractures are negligible and they are not considered in this study,
2. The total gas quantity monitored before and after a fracturing operation in an underground coal mine already includes the gas released by natural fractures. Therefore, it is assumed that any variation of total gas quantity/concentration monitored is only contributed by the artificial fractures created by water jet fracturing.

Based on the assumptions mentioned above, the time-dependent closure behavior of artificial fracture created by the water jet slotting technique is studied in hard (Protodyakonov coefficient, f = >1.5) and soft (f < =1) coal seams respectively, with respect to various slotting parameters and geological conditions.

6. RESEARCH METHOD AND NUMERICAL MODEL

During the water jet slotting operation, some controllable factors, such as, artificial fracture length, width and distance between two fractures, are important in influencing the rheological closure characteristics of artificial fracture created by the water jet slotting system.

On the other hand, due to the coal seam in the natural environment is complex with stochastic uncertainties and imperfections to different extent, and these imperfections are displayed as bedding planes, joints, shear zones and faults, which make the coal seam to be a combined continuum and discontinuum characterizations. In addition, the nature of a coal seam may also vary with different stress conditions induced by the tectonic and mining activities.

Due to the reasons mentioned above, the experimental investigation on the rheological closure of artificial fracture in coal seam is extremely difficult. Therefore, a numerical modeling method is selected in this study.

Numerical simulation of the fracture process in rock requires robust numerical methods that can allow the efficient resolution of multiple interacting cracks and rigorous fracture models that can reflect the material fabric characteristics. In fact, a large number of numerical methods and fracture models have been developed for research on the rock fracture process. The numerical methods most widely used for analysis of the rock fracture process in rock engineering are the finite difference method (FDM) (Fu et al., 2013), finite element method (FEM) (Cai and Kaiser, 2004), boundary element method (BEM) (Li and Chen, 2006) and discrete element method (DEM) (Nagel et al., 2011).

Even other numerical methods are also suitable for this study, such as FEM. But comparatively, the FEM is more suitable for using in soil environment, and FLAC3D(FDM) is more suitable for simulating the complex geometrical conditions in rock environment, which is much more close to the requirements of current study.

6.1. FAILURE CRITERIA FOR TIME-DEPENDENT MODELING

FLAC3D provides many built-in constitutive models that can be employed to simulate the complicated mechanical and time-dependent behaviors of different kinds of soils and rocks. For the time-dependent simulation, there are eight models can be implemented in the FLAC3D.

Rock and coal are the common solid materials in nature, and their mechanical behavior can be described using Hooke's law (William, 2012) under general conditions. On the other hand, when time and stress factors have been taken into consideration, the rock or coal will present rheological characteristics, which may directly influence the coal seam permeability and the efficiency of coal seam gas drainage.

Generally, the rheological characteristics of rock and coal have been often described using creep models, such as the Maxwell model (Jiang et al., 2009; Zhu et al., 2006), the Cvisc model (Liu et al., 2010; Jiang et al., 2008) and the Burgers model (Huang et al., 2006), etc.

In order to represent the rheological characteristics of coal material, the viscous model is selected. The viscous model is the classical formulation known as the Maxwell material, which is constructed by a spring and a dashpot in serial. From a material property point of view, in this model, the Maxwell material is defined as viscoelastic material, which has the mechanical properties both of elasticity and viscosity.

The Maxwell model can be represented by a purely viscous damper and a purely elastic spring connected in series. Under an applied axial stress, the total stress, σ_{total} and the total strain, ε_{total} can be defined as follows:

$$\sigma_{total} = \sigma_D + \sigma_S \tag{2}$$

$$\varepsilon_{total} = \varepsilon_D + \varepsilon_S \tag{3}$$

Where the subscript *D* indicates the stress/strain in the damper and the subscript *S* indicates the stress/strain in the spring. Taking the derivative of strain with respect to time, we obtain:

$$\frac{d\varepsilon_{total}}{dt} = \frac{d\varepsilon_D}{dt} + \frac{d\varepsilon_s}{dt} = \frac{\sigma}{\eta} + \frac{1}{E}\frac{d\sigma}{dt} \tag{4}$$

Where E is the elastic modulus and η is the material coefficient of viscosity. This model describes the damper as a Newtonian fluid and models the spring with Hooke's law.

On the other hand, in order to properly represent the rheological deformation behavior of the underground structure associated with mining, the Cvisc model is selected. The model combines features of Burger model and Mohr-Coulomb model, and suitable for the underground structure in high stress conditions induced by the great depth of mining.

A Cvisc model, also called a Burger-creep viscoplastic model in FLAC3D, is characterized by a visco-elasto-plastic deviatoric behavior and an elasto-plastic volumetric behavior. The viscoelastic and viscoplastic strain - rate components are assumed to act in series. The viscoelastic constitutive law corresponds to a Burger model (Kelvin cell in series with a Maxwell component), and the plastic constitutive law corresponds to a Mohr-Coulomb model (User's guide, 2002).

The main assumption of this model is to split the mechanical behavior of the material into volumetric and deviatoric components. In terms of strain one as (Itasca, 2006):

$$\varepsilon_p = \varepsilon_p^e + \varepsilon_p^p \tag{5}$$

$$\boldsymbol{e}_{ij} = \boldsymbol{e}^{ve}{}_{ij} + \boldsymbol{e}^{p}{}_{ij} \tag{6}$$

Where ε_p is plastic strain, ε_p^e is elastic volumetric strain, ε_p^p is plastic volumetric strain, $\boldsymbol{e}_{ij}$ is deviator of strain tensor, $\boldsymbol{e}_{ij}^{ve}$ is viscoelastic deviator of strain tensor, $\boldsymbol{e}_{ij}^{p}$ is plastic deviator of strain tensor.

The volumetric behavior is only elasto-plastic and is governed by the linear elastic law and the plastic flow rule, while the deviatoric behavior is visco-elasto-plastic and is driven by Burgers model and the same plastic flow rule.

The viscoelastic part can be described by the following relations, which hold true for the Kelvin element (superscript K) and for the Maxwell element (superscript M) respectively. These relations form, in series, the Burgers model.

$$\boldsymbol{e}_{ij}^{ve} = \boldsymbol{e}_{ij}^{veK} + \boldsymbol{e}_{ij}^{evM} \tag{7}$$

Kelvin element:

$$\boldsymbol{s}_{ij} = 2G\boldsymbol{e}_{ij}^{veK} + 2\eta^K \boldsymbol{e}_{ij}^{evM} \tag{8}$$

Maxwell element:

$$\dot{e}_{ij}^{veM} = \frac{\dot{s}_{ij}}{2G^M} + \frac{s_{ij}}{2\eta^M} \tag{9}$$

Where $\boldsymbol{e}_{ij}^{evK}$ is viscoelastic Kelvin value, $\boldsymbol{e}_{ij}^{evM}$ is viscoelastic Maxwell value, s_{ij} is deviator stress tensor, G is shear modulus, η is dynamic viscosity.

The elastic strain component of the volumetric behavior is described by the relation:

$$\boldsymbol{p} = \boldsymbol{K}\varepsilon_p^e \tag{10}$$

Where, K is bulk modulus and elastic volumetric strain. The plastic strains follow the general flow rule of the plasticity:

$$\dot{\varepsilon}_{ij}^{p} = \lambda \cdot \frac{\partial g}{\partial \sigma_{ij}} \tag{11}$$

Where λ is the plastic multiplier and g is the plastic potential, with the same shape as the Mohr-Coulomb yield criterion, but controlled by the dilation angle ψ. The model is characterized by nine parameters, presented in the Tables 1 and 2 for hard and soft coal seams respectively.

6.2. NUMERICAL MODEL OF COAL SEAM FRACTURE CLOSURE

It is considered that the key issues in matching numerical models to rock engineering problems are three main aspects: a) identifying the mechanisms, variables and parameters that are relevant to a particular rock engineering project; b) establishing the content and mode of operation of a particular code; and c) deciding whether a particular code provides an adequate model for a particular project (Harrison and Hudson, 2003).

The time-dependent model (Fig. 1) is developed herein to understand the effect of varied slotting and geological parameters on the closure behavior of artificial fractures in hard/soft coal seams. For this approach, geological and rheological data (Table 1) for hard and soft coal seams determined by Lu (2009) and Lu at al. (2011) respectively.

The properties used in the model development are obtained in two ways, that is, the experimental work, such as the UCS, tensile strength, shear strength, density, cohesion, friction angle, etc and the theoretical determination, such as, K_{shear}, $K_{viscosity}$ and $M_{viscosity}$, etc. All the parameters applied to the model are adjusted with field data collected, so as to eliminate the errors caused due to the selection of values and make sure the model represents the actual behavior observed in the field well.

7. CALIBRATION AND VALIDATION OF NUMERICAL MODEL

The purpose of validation is to quantify and build confidence (or credibility) in numerical models, and is an enabling method for the development of computational models that can be used to make engineering predictions with quantified confidence (Thacker et al., 2004).

Validation is the process of determining the degree to which a model is an accurate representation

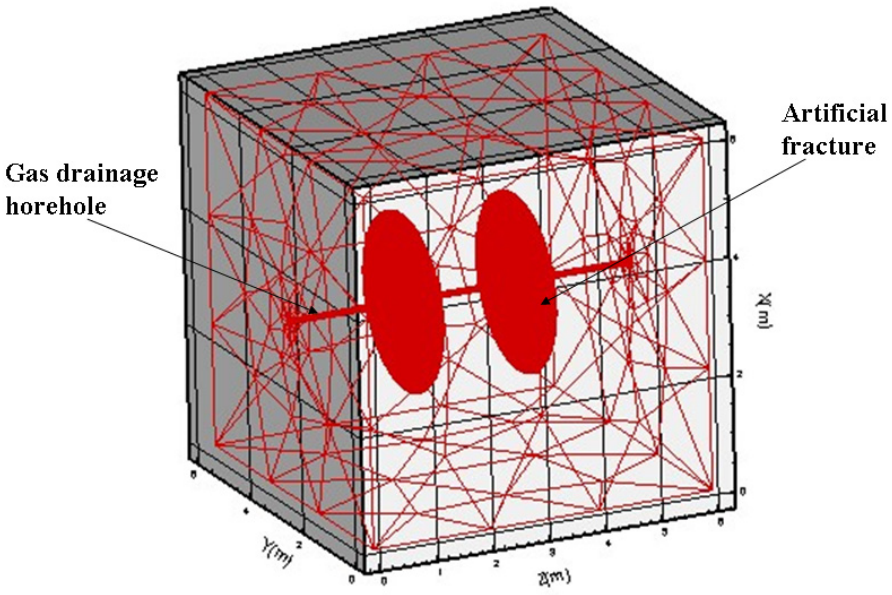


Fig. 1 Numerical model for time-dependent simulation of fracture closure.

Table 1 Geomechanical and rheological data assigned for hard and soft coal models.

Properties	Hard coal	Soft coal
Tension (MPa)	1.164	0.025
Shear (MPa)	2.8	0.14
Bulk (GPa)	3.91	0.25
Density(kN/m^3)	13.63	13.8
Cohesion (MPa)	6.53	0.03
Friction angle(°)	30.7	38
K_{shear} (GPa)	6.03	2.64
$K_{viscosity}$(GPa.s)	9.32	6.12
$M_{viscosity}$ (GPa.s)	10.1	7.1

Table 2 Waterjet slotting parameters used for hard and soft coal seams.

Parameters	Mining depth	Slotting distance	Slotting thickness	Slotting radius
Hard coal	240 m	1 m	4 cm	0.5 m
Soft coal	150 m	1 m	4 cm	0.5 m

of the real world from the perspective of the intended uses of the model, and it is concerned with quantifying the accuracy of the model by comparing numerical solutions to experimental data. Table 2 shows the slotting parameters used in the hard and soft coal seams.

The model related to the hard and soft coal seams is calibrated using gas drainage data collected separately from two underground coal mines by adjusting geomechanical and rheological parameters assigned to the model.

For the hard coal seam, the boreholes drilled in underground were 40 m in length and the water jet slotting was applied in 1m interval along the length of gas drainage borehole. Therefore, the variation of one fortieth total gas quantity collected from underground monitoring is used to calibrate the closure of a single artificial fracture with time, the result shown in Figure 2 is acceptable. On the other hand, due to the gas quantity fluctuated with time, it is impossible to exactly match both field and modeling data by adjusting the geomechanical and rheological parameters.

In the soft coal seam, the gas drainage boreholes were 15 m in length and the waterjet slotting was applied in 1 m intervals along the length of the borehole. Similarly, one fiftieth of the gas concentration detected by a sensor from the developing face of excavation in the underground is used to calibrate the model of the closure of a single artificial fracture. Same as the first model discussed above, there are errors occurred due to the sensitivity

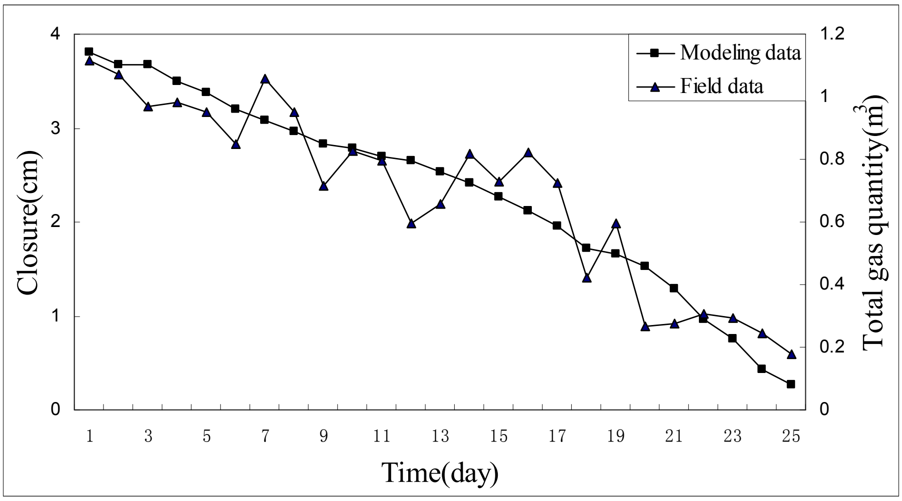


Fig. 2 Model validations for hard coal seam.

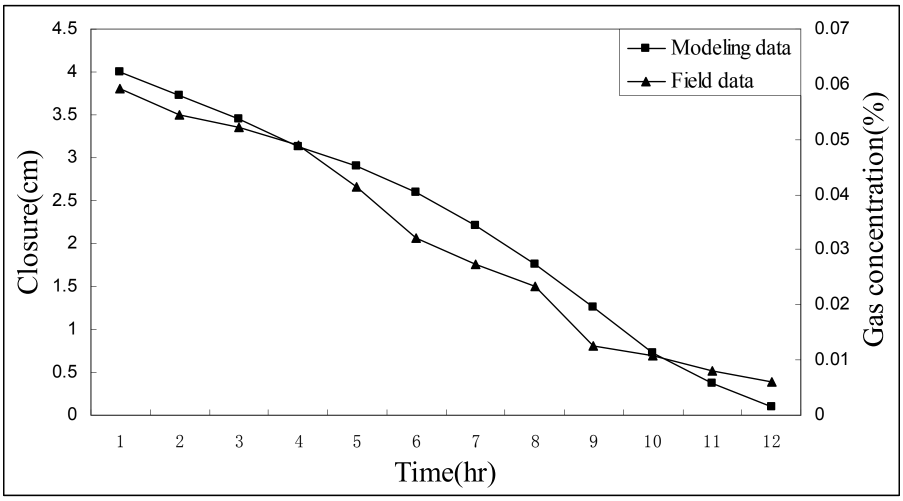


Fig. 3 Model validations for the soft coal seam.

of geomechanical and rheological parameters used. But the results presented in Figure 3 indicate that the numerical model developed is accurate enough to represent closure behavior of artificial fracture in the soft coal seam condition.

8. MODELING RESULTS OF TIME-DEPENDENT CLOSURE BEHAVIOR ASSOCIATED WITH SLOTTING PARAMETERS

Most coal seams possess fractures and other discontinuities, which facilitate the movement of coal seam gas through them. The previous study indicated that the significant roles of fracture geometry and water-content on permeability of coal seam (Wang et al., 2011). On the other hand, when the waterjet slotting system is used to increase coal seam permeability, the geometrical parameters of artificial fracture created by waterjet system, such as slotting radius, slotting width, slotting distance, may be manipulated and controlled on the basis of characteristics of gas content, geological conditions and operation requirements, etc. Thus, the controllable geometrical parameters of artificial fractures (Fig. 4), including fracture length (slotting radius x 2), fracture width (slotting thickness) and fracture distance (slotting distance) are investigated to understand how these parameters affect the closure characteristics of artificial fractures in both hard and soft coal seams.

8.1. TIME-DEPENDENT CLOSURE BEHAVIOR ASSOCIATED WITH FRACTURE LENGTH

For the waterjet slotting fracturing technique, the slotting radius or fracture length is a key parameter, which demonstrates the capacity of the slotting system. Also the slotting radius represents the length of the fracture created within the coal seam.

Previous laboratory researches indicated that the permeability increases proportionally with the length of fracture (Long et al., 1985).

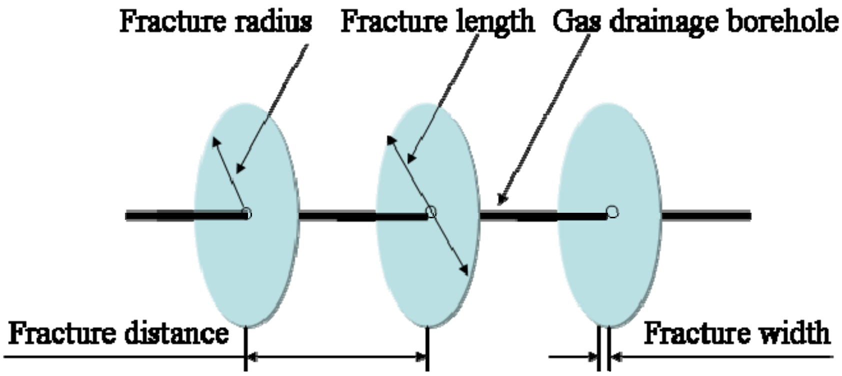
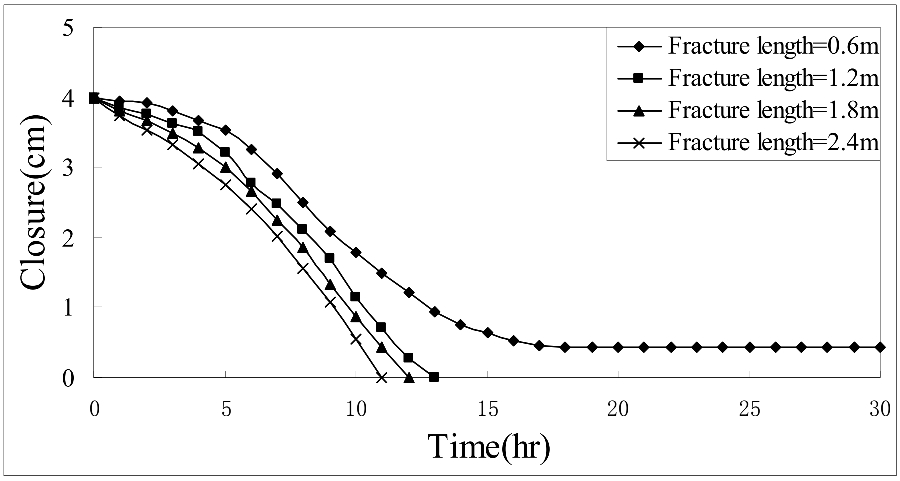
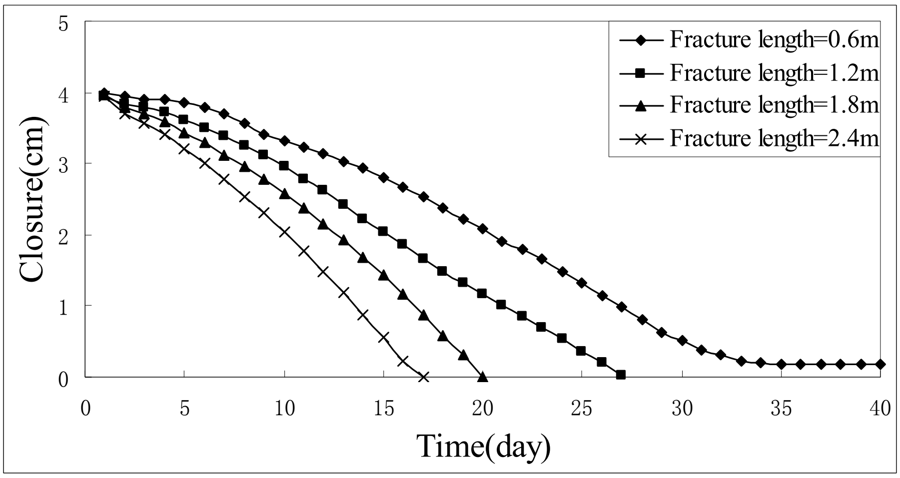


Fig. 4 Controllable fracture parameters created by waterjet system.



a) Soft coal seam

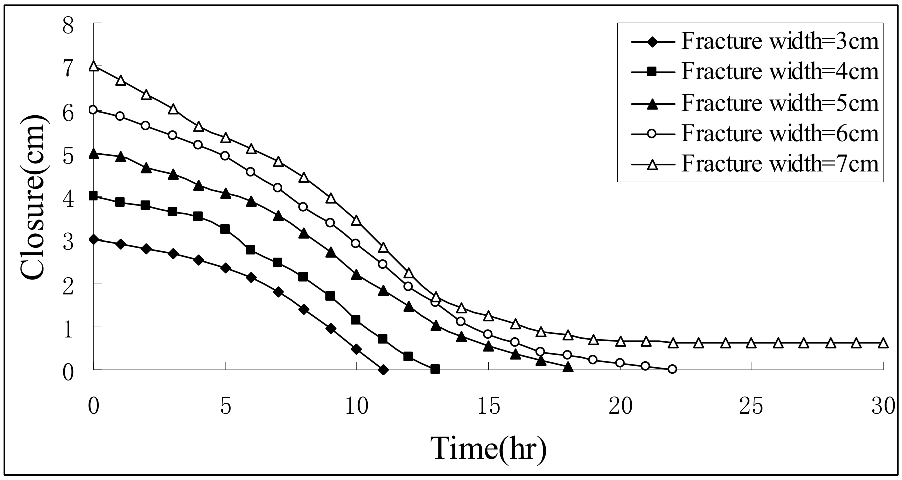


b) Hard coal seam

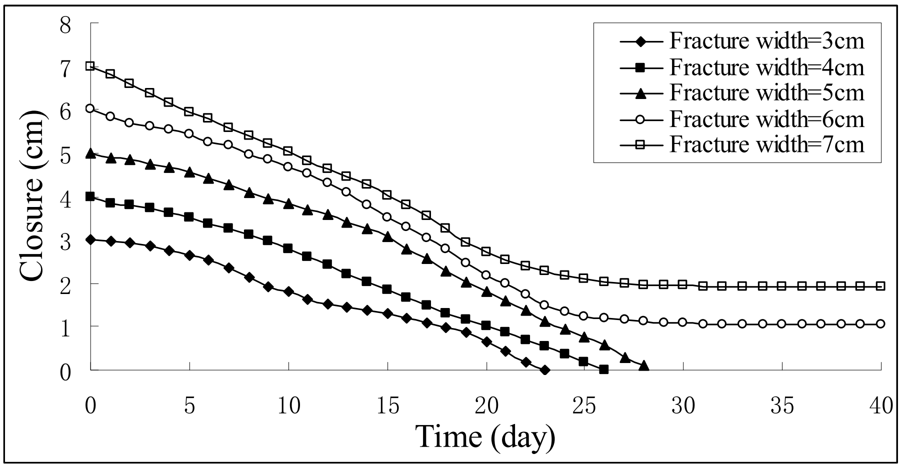
Fig. 5 Time-dependent closure characteristics associated with fracture length.

In order to understand how the length of the artificial fracture affects the characteristics of closure, four levels of fracture length have been designed for simulation in the hard and soft coal seams, including 0.6 m, 0.9 m, 1.2 m and 2.4 m.

The time-dependent closure behavior and corresponding data of artificial fractures associated with fracture length in soft and hard coal seams have been presented in Figure 5.



a) Soft coal seam



b) Hard coal seam

Fig. 6 Time-dependent closure characteristics associated with fracture width.

According to the modeling results, following results can be determined as:

- Coal strength is a sensitive parameter, which significantly affect the closure behavior of fracture created in coal seam. The results indicated that higher the coal strength, the longer the fracture remains open,
- With increasing fracture length, the fracture will close more quickly, and vice versa.

8.2. EFFECT OF FRACTURE WIDTH ON TIME-DEPENDENT CLOSURE CHARACTERISTICS

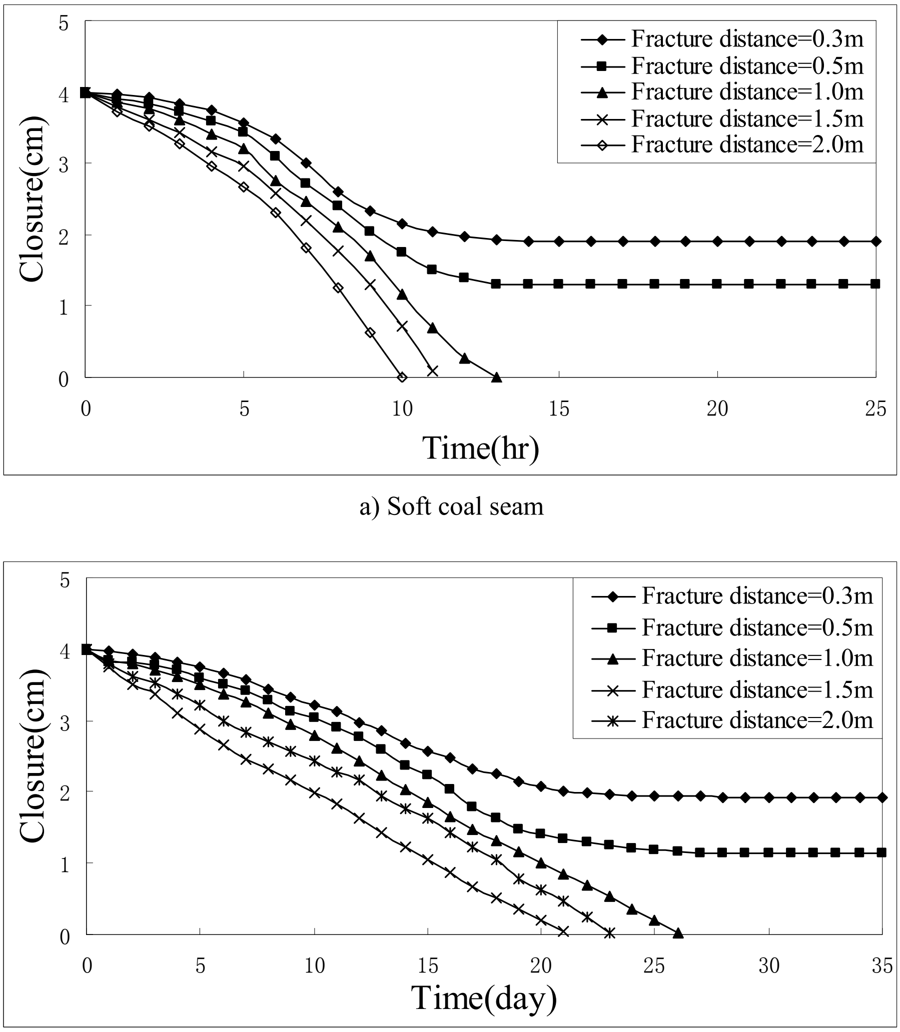
Theoretically, permeability can be calculated using Eq. 1 mentioned in previous section. It is a much more dependent on the cleat width b than the matrix block width s because of the cubic exponent attached to b (Robertson and Christiansen, 2006.). It implies that the fracture width is a sensitive and important parameter for coal seam permeability. Thus, different levels of fracture width, varying from 3 cm to 7 cm are selected respectively for the simulation. Modeling results are presented in Figure 6 for soft and hard coal seams.

From Figure 6, it is noted that the residual fracture width may be obtained when 7 cm of fracture width is selected in soft coal seam, and 6 cm of fracture width is selected in hard coal seam.

8.3. EFFECT OF FRACTURE DISTANCE ON TIME-DEPENDENT CLOSURE CHARACTERISTICS

Practical experiences indicated that the permeability of coal seam improves with the increase of fractures formed within the coal seam. In order to quantify this concept, fracture density is used. It is defined by Dershowitz and Herda (1992) as “the area of fractures in a volume” of rock.

The distance between fractures is inversely proportional to fracture density. So, the distance between fractures represents the frequency of fracture,



a) Soft coal seam

b) Hard coal seam

Fig. 7 Time-dependent closure characteristics associated with fracture distance.

it is simply the number of fractures intersecting per unit length of the borehole, and is one of the important parameters relating to not only gas drainage, but also the closure of fractures created. This parameter can be designed during the waterjet slotting application on the basis of coal strength, stability of borehole, time consuming of slotting, permeability of coal seam, etc. The simulation conducted in this section attempts to understand how the distance between two fractures influences the closure characteristics of fractures. To do so, the distances between two fractures are selected as 0.3 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m respectively, and the results are given in Figure 7.

The distance between two fractures also represents the density of fracture along the length of borehole, that is, the smaller of the fracture distance, the higher of fracture density. The modeling results presented above indicated:

- When fracture distance is smaller enough, in current case, 0.5 m, the fracture may remain opening in longer time,
- In other word, if the fracture density is large enough, or the distance between fractures is small enough, the fracture created by the water jet system may remain opening in relative long time.

The modeling results presented above also indicated that the increase in the gas drainage efficiency due to the fracturing treatment not only depends upon the closure behavior of fractures, but also the residual opening of the fracture which incorporates the length, width and distribution of the fracture along the length of borehole.

The residual fractures are directly linked to the fracture conductivity and, therefore, represent the main outcome of fracture stimulations. It also significantly affects the productivity of reservoirs and, finally, determines the success of the stimulation procedures (Neto and Kotousov, 2013).

Generally, the existence of residual fracture in the modeling results given in the previous sections, may be related to many factors, such as, the stress conditions of coal seam, the geomechanical characteristics of coal seam, the time elapse after stimulation, and the stimulating method and parameters selected, as well as the model calibration data used during the model development.

According to the modeling results, the residual fractures remained are due to the geomechanical characteristics of coal seam (soft and hard coal), slotting parameters selected, the closure behavior of fractured created by using waterjet slotting technique, which matched well with the gas data variation monitored.

9. TIME-DEPENDENT CLOSURE CHARACTERISTICS AND MECHANISMS OF ARTIFICIAL FRACTURES AND THEIR IMPLICATIONS FOR EFFICIENCY OF GAS DRAINAGE

The coal seam permeability of an artificial fracture may decrease with time due to time-dependent closure associated with parameters of the fracturing technique used, in-situ stress conditions and coal ranking.

9.1. EFFECT OF SLOTTING GEOMETRIES ON TIME-DEPENDENT CLOSURE AND THEIR IMPLICATIONSFOR GAS DRAINAGE

Length and width determine the geometrical features of an artificial fracture. The work in this section is to clarify how varying geometrical parameters, such as the fracture length and width influence the closure behavior of a fracture and coal seam permeability.

The results shown that the longer the fracture, the quicker the closure of the fracture will occur. This phenomenon may be explained by using the simple support beam theory, in which, the deflection (closure) can be determined as:

$$\omega_C = \frac{5ql^4}{384EI} \tag{12}$$

Where ω_c is the deflection of the beam, the *EI* is stiffness of the beam, *q* is the uniformly distributed load (normal compressive stress), and l is the length of the beam. In Eq.12, the length l is the most influential parameter to the deflection (closure of the fracture) and it increases with the span increased. It implies that the rate of closure may be properly controlled by adjusting the fracture length during the underground application of the waterjet fracturing.

Traditionally, it is considered that a longer fracture created in the coal seam has more advantage than short one, as it may increase the coal seam permeability and improve the efficiency of gas drainage. But the modeling results indicate that a longer fracture may close in a relatively short period of time, which has been proven by previous experimental work (Giwelli et al., 2009) and it is particularly true in a soft coal seam. The modeling results indicated that different fracture lengths may give different gas drainage results, so, it is important to rationally design a fracture length (slotting radius) based on the gas drainage characteristics and mining plan.

Where fracture width is concerned, it is noted that an artificial fracture created will remain open in a soft coal seam with 1cm of residual fracture, when the artificial fracture was originally designed with a width of 7 cm. Similarly, in a hard coal seam, when the artificial fracture is designed with a width of 6 cm or above, a 1.5 cm residual fracture is all that will be remain with time. It is noted that the residual fracture width will increase with an increasing of the initial fracture width. The modeling results proved the previous research conclusion, that is, the trend and magnitudes of flow rate variations are controlled by the initial magnitudes of fracture apertures, external load configurations and rock deformations (Zhang et al., 2007).

It may also explain the phenomenon that the efficiency of gas drainage can be maintained briefly after the application of the hydraulic fracturing technique, as the width of fracture created by hydraulic fracturing is not large enough, so it is difficult for it to remain open with time, particularly in a soft coal seam.

Accordingly, during waterjet fracturing, the fracture width should be designed as large as possible, so as to maintain a relatively longer period of high efficiency of gas drainage.

9.2. EFFECT OF FRACTURE DISTANCE ON TIME-DEPENDENT CLOSURE AND ITS IMPLICATIONS FOR GAS DRAINAGE

The distance between two fractures created artificially during the waterjet fracturing may relate to two issues. First, the influence of two adjacent fractures due to stress redistribution around the fracture, which may affect the closure behavior of the fracture; second, the frequency of fractures created artificially along the length of borehole, which may change the permeability of coal seam.

Previous research (Lu et al., 2011) indicated that, after the formation of a fracture created by the waterjet fracturing technique, the stress around fracture is redistributed. When two fractures are designed close enough, e.g. less than 0.5 m, the stress released regions around two fractures may coincide (Fig. 8), and it results in the normal stress, which is one of the major factors controlling the closure behavior of a fracture, being reduced significantly, so the fracture will remain opening or close slowly with time.

When the distance between two fractures is larger than 0.5 m, there is no coincidence occurring between two fractures and the fracture will be sustain higher stress than the situation mentioned above, so the fracture will close relatively fast with time.

In general, the rate of closure will increase with the increase of distance between two adjacent fractures created or the frequency of fracture.

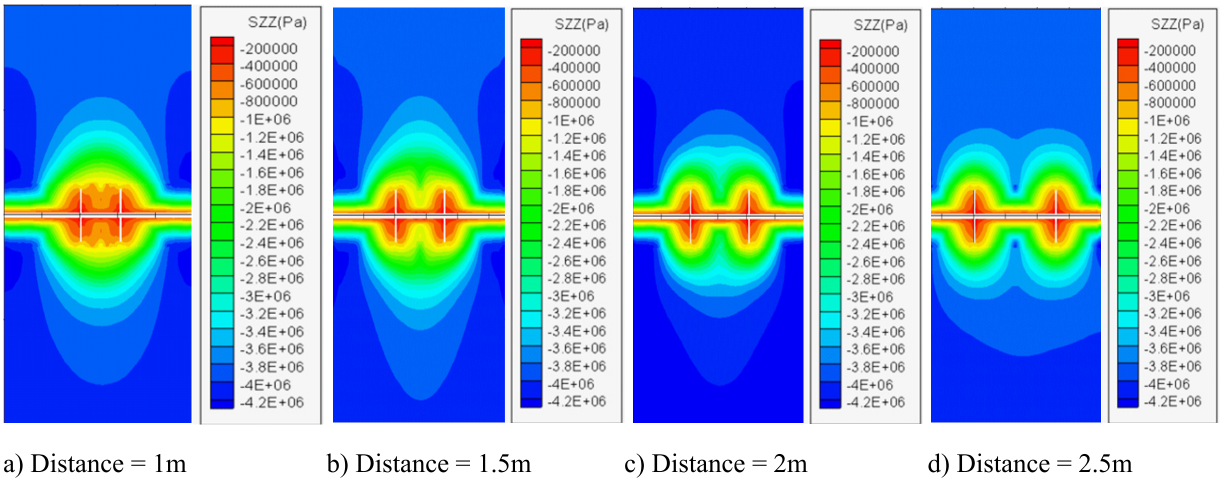


Fig. 8 Stress redistribution around fracture with different fracture distances (after Lu et al., 2011).

The fracture density plays an important role in the increase or decrease of the overall conductivity of the system. Previous research indicates that density increases by adding more fractures to the dataset, and a minimal change in density causes a surge of the conductivity in the system (Paluszny, 2009).

Apparently, with the increase of the density of fracture, the coal seam permeability increases. On the other hand, after creating fractures artificially, a bunch of stress relief zones are formed along the length of borehole. Within those zones, the confining pressure is reduced considerably, and results in an increasing of coal seam permeability.

10. CONCLUSIONS

The time-dependent closure characteristics of fractures created artificially using the highly pressurized waterjet fracturing technique has been studied numerically using Flac3D on the basis of field monitoring data collected from soft and hard coal seams in different mines and its implications for coal seam permeability has been analyzed accordingly.

Firstly, the modeling results indicated that a long fracture may close quickly, and increasing fracture width is a more effective way to maintain coal seam permeability.

Secondly, the frequency of fracture is directly related to the permeability of coal seam and the stress regime around the fracture created. The modeling results indicated that when two fractures are close enough, in current case, 0.5 m, the stress regime formed around fracture may benefit for keeping the fracture open.

On the other hand, the modeling results implied that the increase in the gas drainage efficiency due to the fracturing treatment not only depends upon the closure behavior of fractures, but also the residual opening of the fracture which incorporates the length, width and distribution of the fracture along the length of borehole.

Existence of residual fracture may be due to many factors, but according to current research, it is related to the geomechanical characteristics of coal seam (soft and hard coal), slotting parameters selected.

Therefore, the closure behaviors, including fracture and residual fractures, may be controlled by properly designing artificial fracture parameters and boreholes associated with geological and geomechanical conditions encountered.

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