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Multiphysics Coupled Modeling of Coal Seam Fracture Stimulation Under Highly Pressurized Gas Impact Loading

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Abstract

3D gas-solid coupled symmetrical numerical model was developed on the basis of multiphysics finite element platform to study coal seam fracture stimulation under the high pressure gas impact loading generated by the highly pressurized multi-discharge carbon dioxide gas fracturing technique to improve pre gas drainage efficiency. The purposes of this study are to understand the natural and operational factors contribute to coal seam fracture stimulation and improvement of coal seam gas drainage efficiency and the interaction of these parameters. The results indicated that the highly pressurized liquid carbon dioxide fracturing technique provides three fundamental functions in improving efficiency of coal seam gas drainage: 1) improving coal seam porosity/permeability and 2) releasing gas adsorbed from coal seam, 3) forming gas pressure gradient of coal seam. Among them, the first function develops/stimulates the coal seam fracture network, the second function releases more free gas for drainage and the third function, as the driving force, mobilizes the gas released from the fracturing borehole to the drainage boreholes through the network developed/stimulated.

Keywords: Modeling; Coal Seam Fracture Stimulation; Gas Drainage; Highly Pressurized Gas; Dynamic Loading

Introduction

Recently, the coal seam fracture stimulation operations using the highly pressurized liquid carbon dioxide fracturing technique have been significantly increased for improvement of coal seam gas drainage efficiency in Chinese coal mining industry. The benefits obtained during these applications are obvious, including: 1) avoiding damage or risk caused by the fly rock due to blasting, 2) making the process of coal mining smoothly in rich methane environment, 3) reducing occurrence of gas explosion in underground coal mine, etc. However, comparing with the field applications, the effect of natural and operational factors on the effectiveness of coal seam fracture stimulation is not clear. Therefore, the numerical modeling has been conducted to study how these natural and operational factors contribute to coal seam fracture stimulation and improvement of coal seam gas drainage efficiency, as well as to clarify the interaction relationships of deformation and failure around borehole well, the fracture formation of internal coal body and gas pressure gradient built up within the coal seam with various levels of high pressure gas impact loading.

About highly pressurized multi-discharge carbon dioxide gas fracturing technique

The highly pressurized single discharge liquid carbon dioxide fracturing technique is modified from the Cardox system (Figure 1), which is designed to break or aerate materials by discharge carbon dioxide at high pressure into the material. In order to operate the system in any material, a range of tubes (containers) are available. In turn, these provide a range of discharge pressures. The combination of various tubes, discharge pressures and chemical energizers (heaters) allow over twenty different discharge characteristics (Cardox User Manual) [1], which gives flexibility to different applications, e.g. coal seam fracture stimulation, outburst control, rock burst control and coal/rock strata destress, etc., as well as different geological and geomechanical conditions in underground of coal mines.

During the underground practices, it is noted that the single discharge system - a standard configuration of the original Cardox system, can not satisfy the requirement of thick coal seam fracture stimulation; therefore, a highly pressurized multi-discharge liquid carbon dioxide fracturing technique has been developed.

The multi-discharge fracturing technique is composed of multiple single discharge fracturing systems, in which, each single discharge fracturing system is connected in series mechanically and electronically. During the coal seam fracture stimulation operation, each individual single discharge system is discharged simultaneously along the length of single borehole, so as to achieve the purpose of thick coal seam fracture stimulation.

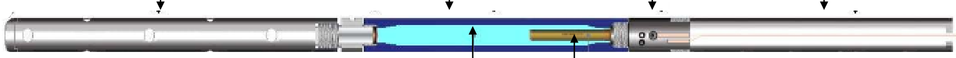


Figure 1: Single discharge liquid CO2 fracturing technique (Modified from Cardox)

Fundamental data collected from field

Current numerical modeling is completely based on a typical condition of field work, including the geological and geomechanical parameters and the gas drainage data monitored.

The typical gas drainage data, including gas concentration and gas flow, has been monitored and collected associating with the coal seam fracture stimulation operations using the highly pressurized multi-discharge liquid CO_2 fracturing technique in Changping colliery, which is located in south of Qinshuei coal field, Jincheng city, Shanxi province, China, where, the coal seam 3# is a main recoverable seam with average thickness of 5.58m.

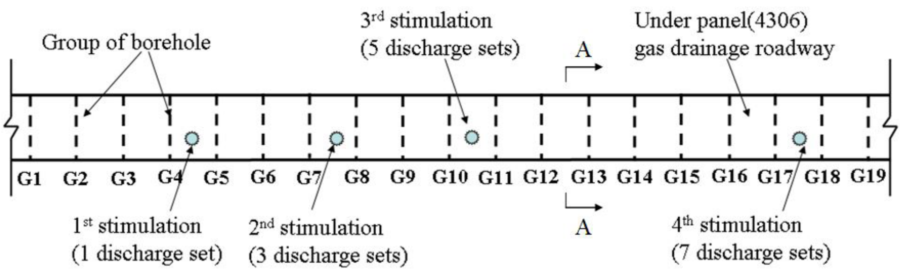
Affected by regional geological structure, the coal seam is characterized by compactness and poor permeability. Historically, the gas drainability in some part of Qinshuei coal field is found to be particularly poor, which posed a significant challenge to pre gas drainage. During the field work, the coal seam 3# presented quite low permeability, and it results in failure of operations to effectively manage longwall gas emission, therefore, it is often occurred that the gas liberated exceeds the dilution capacity of the mine ventilation system. In such situations, the gas concentration in the mine airway exceeds the prescribed statutory limit resulting in a production delay until such time as the concentration is reduced.

Under such circumstance, it is impossible to conduct gas drainage operation effectively by using a traditional drainage method in a relatively short period of time. A typical response of colliery operator in such case is to employ the highly pressurized multi-discharge liquid carbon dioxide fracturing technique to increase coal seam permeability and improve single borehole gas drainage rate and prolong time of stable gas drainage in coal panel.

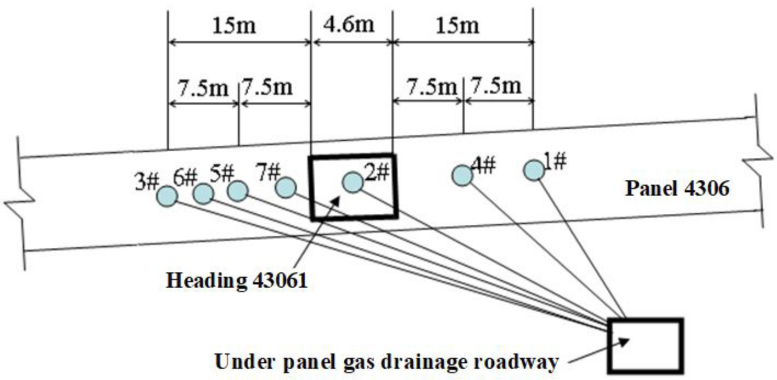
Brief description of field operation and data collection

Considering the mining layout and the thickness of coal seam, the under panel cross strata drilling and coal seam fracture stimulation have been proposed and implemented in the under panel gas drainage roadway, which is a roadway under the coal panel and dedicated for coal seam fracture stimulation and gas drainage operation. Pre drainage at the under panel gas drainage roadway is one of the widely used comprehensive gas manage methods in Chinese coal mining industry.

Figure 2 shows the under panel cross strata drilling design and coal seam stimulation arrangement. Figure 2a shows borehole drilling layout, where 19 groups of borehole with 5m interval are set up along 100m trial section. The detailed under penal cross strata drilling design for each group is given in Figure 2b. Even many important parameters can be obtained according to the design, only influential radius of gas drainage due to fracture stimulation is interested in for current work, which will be used for model verification.



a) Trial section arrangement (top view)



b) Under panel 4306 cross strata drilling design(A-A section)

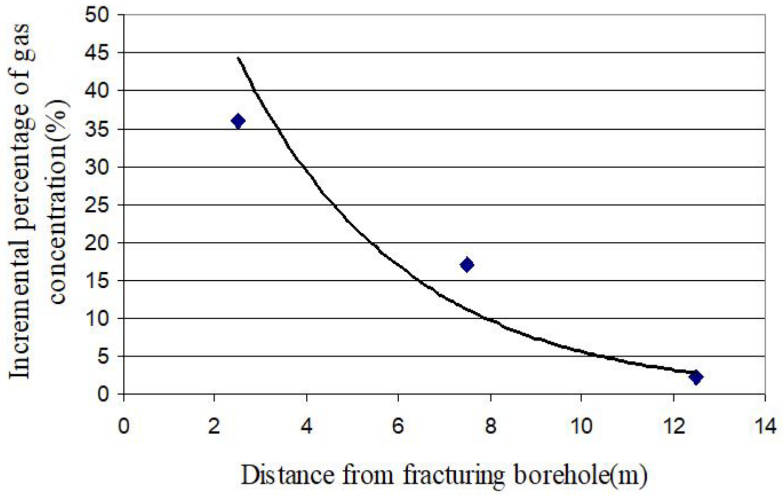
Figure 2: Coal seam fracture stimulation arrangement

On the basis of above mentioned design, the operating procedure of coal seam fracture stimulation and gas data collection is given below:

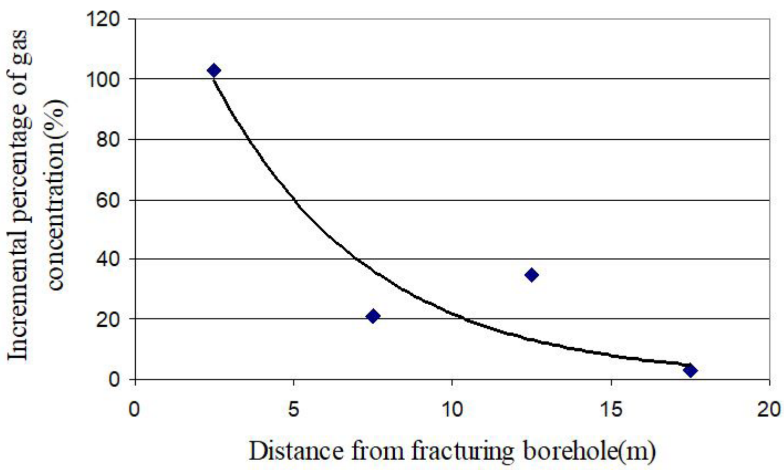
1) Each group of borehole is drilled along the length of trail section,
2) Gas data, including gas concentration, total gas quantity and pure gas quantity of each borehole are collected immediately and then the data will be recorded once a day,
3) When attenuation of borehole gas concentration occurs, first fracturing borehole is drilled between borehole groups 4# and 5# (Figure 2a),
4) Then, coal seam fracture stimulation with single discharge set is performed after formation of the fracturing borehole, and followed by gas data collecting and monitoring for all boreholes along the length of trail section,
5) When attenuation of borehole gas concentration occurs again, the similar operating procedure will be implemented between groups 7# and 8# with three discharge sets used, and between groups 10# and 11# with five discharge sets used, as well as between groups 17# and 18# with seven discharge sets used respectively.

Drainage radius induced by fracture stimulation with different discharge sets

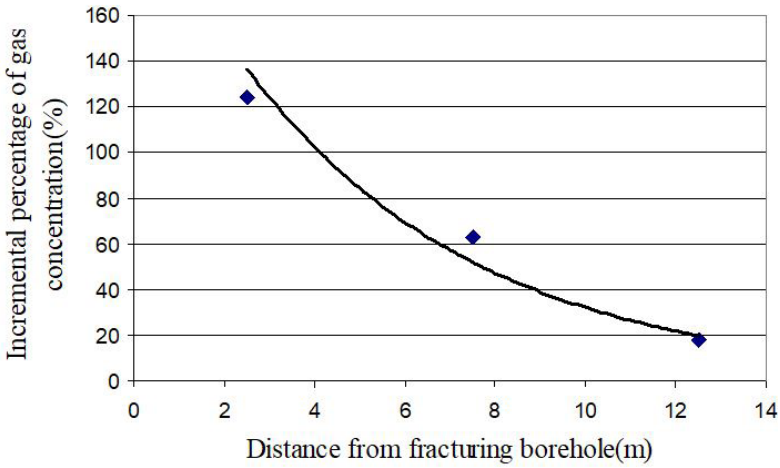
For a gas drainage operation, the effective drainage radius is defined by a boundary where gas drainage quantity begins to significantly decline, and it also determines the distance between two adjacent gas drainage boreholes to be selected during the gas drainage designation.



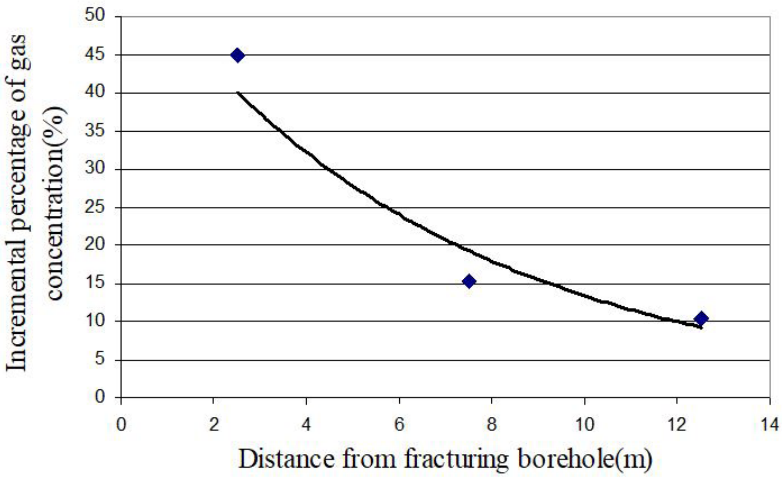
a) One discharge set



b) Three discharges sets



c) Five discharge sets



d) Seven discharges sets

Figure 3: Incremental percentages of gas concentration with various numbers of discharge sets

To precisely determine the drainage radius induced by fracture stimulation, the incremental percentage of gas concentration of equidistant groups on both sides of the fracturing borehole, including 2.5m, 7.5m, 12.5m and 17.5m, are calculated and presented. Figure 3 shows the average incremental percentage of gas concentration at the same distance on both sides of the fracturing borehole with one, three, five and seven discharge sets used respectively.

According to the data given in Figure 3, it clearly shows the gas drainage radius and its trend of variation induced by the fracture stimulation, and these data will be used for model verification.

Effect of natural and operational factors on coal seam fracture stimulation

Currently, the highly pressurized liquid carbon dioxide fracturing technique has been widely used in Chinese coal mining industry for coal seam fracture stimulation and improvement of gas drainage efficiency. The results of engineering practice indicated that the technique is safe in rich methane environment and effective for coal seam fracture stimulation in underground coal mine. However, comparing with the field applications, the effect of natural and operational factors on effectiveness of coal seam fracture stimulation is not clear.

Approach and purposes

A multi-physical gas and solid coupled three dimensional numerical model associated with the field data collected is developed using a commercial software, COMSOL multiphysics, so as to gain insights into the interaction of high pressure gas impact loading and coal seam fracture development, and clarify the effect of controllable and uncontrollable factors on coal seam fracture stimulation, and improvement of coal seam gas drainage efficiency.

About COMSOL multiphysics

The coupling between gas flow and solid deformation in porous media, which is a principal geo-material to deal with in underground coal mining, has received a considerable attention because of its importance in the area of multi-physical field analysis, contaminant transport and gas outburst during coal mining.

COMSOL is a multiphysics modeling tool that solves various coupled physical problems based on Finite Element Analysis and Partial Differential Equations, which provides a user-friendly interface for mesh generation, equations configuration, and results visualization (Shao et al, 2014) [2]. The model can be built with user-defined equations or discipline-specific modules, in here, coupled gas and solid model with dynamic impact loading has been selected. The Subsurface Flow Module and Solid Mechanics Module are applied for modeling the coupled hydrological and soil mechanical system respectively.

Fundamental assumptions

Coal is a porous medium with the gas formed during the formation; it presents heterogeneous characteristics, due to tectonic effect. However, from the macroscopic point of view, for a same geological unit, coal may be considered to have the same physical and chemical properties, so, it may be approximately regarded as homogeneous. To simplify the field conditions, it is necessary to make the following assumptions for numerical simulation as follows:

1) Considering the significant difference between the highly pressurized gas impact loading applied on the coal seam and the internal gas pressure within the coal seam, it is regarded that the permeability of coal seam is not affected by the change of original gas pressure in coal seam.

2) Considering the mechanical properties of roof and floor strata of coal seam, the permeability is far less than that of coal seam, so the roof and floor are regarded as impermeable.

3) Due to the amount of carbon dioxide gas injected into the coal seam is relatively small, after discharge of the highly pressurized liquid carbon dioxide gas fracturing technique, the replacement effect of carbon dioxide on coal seam gas is ignored.

Governing equations for gas-solid coupling model

The gas and solid coupling modeling is conducted to study the interaction of in-seam gas distribution characteristics (fluid mechanics), porosity and permeability of coal seam, as well as deformation and failure of borehole wall(solid mechanics) with the high pressure gas impact loading, therefore, the model involves fluid mechanics governing equations and solid mechanics governing equations in porous medium.

For fluid mechanic governing equations, which are used in here to control in-seam gas movement and gas pressure distribution, there are two types of control equations included, that is, the seepage control equation and the gas state equation.

The seepage control equation. There are two assumptions have been taken into consideration, including 1) the gas movement within coal seam obeys Darcy's law, and 2) ideal gas has been considered for coal seam gas and the gas movement is treated as an isothermal process, so there is (Mo, 2014) [3]:

$$\frac{\partial Q}{\partial t}+\nabla\cdot(\rho\cdot v)=0 \quad (1)$$

or

$$v_D=-\frac{k}{\mu}\nabla p=-\frac{k_j}{\mu}p \quad (2)$$

Where, ρ is density of coal seam gas, kg/m^3 r is velocity of seepage, m/s, Q is gas contain of coal seam, kg/m3, μ is kinetic viscosity of coal seam gas, v_D is Darcy seepage velocity tensor, and k is permeability tensor.

The gas state equation. This equation defines the relationship amount gas density, pressure and temperature. Under the condition of constant temperature, the coefficient of gas compressibility is determined as (Wang, 2014):

$$\alpha_f=-\frac{1}{V_f}\frac{\partial V_f}{\partial p} \quad (3)$$

Where, V_f is gas volume, and p is gas pressure. According to mass conservation law, $m_f = r_f V_f = constant$, $dm_f = V_f dmf + V_f dV_f = 0$, there is:

$$dm_f=-V_f\frac{d\rho_f}{\rho_f}=dV_f=0$$

Combining Eqs.(2) and (3) :

$$\alpha_f=\frac{1}{\rho_f}\frac{\partial\rho_f}{\partial p} \quad (4)$$

Integrating Eq.(4), the relationship between gas pressure and gas density at constant temperature, also called state equation of gas, can be derived as:

$$\rho_{\mathrm{f}}=\rho_{f0}\exp[\alpha_f(p-p_0] \quad (5)$$

Where, ρ_{f0} is gas density with initial gas pressure p_0. On the other hand, the coefficient of gas compressibility can be represented by using bulk modulus of elasticity as:

$$K_f=\frac{1}{\alpha_f} \quad (6)$$

Combining Eqs(6) and (7), the gas state equation of coal seam can be written as:

$$\rho_f=\rho_{f0}\,exp\left[\frac{1}{K_f}(p-p_0)\right] \quad (7)$$

For solid mechanics governing equations, which are used to control and analyze the variation of porosity and permeability of coal seam as well as deformation and failure of borehole wall and coal seam under high pressure gas impact loading. There are four types of control equations included, such as, 1) solid equation of internal structure, 2) porosity control equation, 3) theoretical model of permeability and 4) deformation equation of coal and rock mass.

Solid equation of internal structure. According to the solid mechanics, the state equation of internal structure of coal body containing methane can be expressed as (Li and Kong, 2003) [4]:

$$\rho_s = \rho_{so}\, exp\left[a_s\left(p - p_0\right)\right] = p_{s0}\, exp\left(\frac{p - p_0}{K_s}\right) \tag{8}$$

Where, ρ_{s0} is density of internal structure of coal body under pressure p_0, 10kg/m^3, p is coal seam gas pressure, MPa, K_s is bulk elastic modulus of gas, Pa, a_s is compressibility coefficient of gas.

Porosity control equation. It is assumed that the coal body contains a single phase saturated gas, and the liner elastic deformation occurs when the loading is applied on the coal body. Accordingly, the porosity (φ) of coal body can be defined as:

$$\varphi = 1 - \frac{\left(1 - \varphi_0\right)}{1 + \varepsilon_V}\left(1 + \frac{\Delta V_s}{V_{s0}}\right) \tag{9}$$

Where, V_s is solid structure volume of porous media, m^3, ΔV_s represents the variation of V_s, m^3, φ_0 is initial porosity of coal seam, and ε_v is volumetric strain of coal body, m^3.

Theoretical model of permeability. Permeability is a parameter, which defines the difficulty of gas movement within coal seam. Normally, the permeability is considered as a constant value in the seepage model, which did not involve the internal structure deformation and variation of porosity of coal body. However, when an impact loading is applied on the coal body, the internal structure and porosity of coal body may be changed significantly, which results in the variation of permeability of coal seam. Under such circumstances, the theoretical control equation for permeability, which defines the relationship between porosity and permeability of coal seam can be described using Kozeny-Carman equation as (Lu and Shen, 2002) [5]:

$$k = \frac{\varphi}{k_z S_p^2} = \frac{\varphi^3}{k_z S_v^2} \tag{10}$$

Where, k_z is constant and equals 5, φ is permeability, S_v is surface area of pores in unit volume of porous media, cm^2, $S_p = A_s/V_p$, A_s is total surface area of coal, cm$_2$, V_p is pore volume of coal, cm^3.

Deformation equation of coal and rock mass. Under an impact loading, the deformation or failure of coal body may occur. Such deformation and failure is defined by using rock mechanics deformation control equation, including geometric equation and constitutive equation respectively.

For geometric equation of coal body deformation, it can be expressed as (Lu, Shen, 2002) [5]:

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) \tag{11}$$

and the volumetric strain is:

$$\varepsilon_v = u_{11} + u_{22} + u_{33}$$

Where, ε_{ij} is stress tensor, ε_v is volumetric strain of coal, u is deformation, m.

For the constitutive equation of deformation and failure of coal body, the deformation is described herein by two parts, elastic strain increment ($d\varepsilon^e_{ij}$) and plastic strain increment ($d\varepsilon^p_{ij}$), that is, the plastic flow rule (Zhou, Li, 2008) [6]:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} \quad (12)$$

The increments between elastic stress and elastic strain are connected by elastic matrix *D*, and the increment of plastic strain is represented by plastic potential energy, so we have:

$$d\varepsilon_{ij}^{p} = \lambda \frac{\partial g}{\partial \sigma_{ij}} \quad (13)$$

Where, λ is positive undetermined limited value. For a stable plastic deformation, normally the hardened material *g* can be represented by similar form of yield function *f*, so the plastic flow rule can be given as:

$$\mathrm{d}\varepsilon_{ij}^{p} = \lambda \frac{\partial f}{\partial \sigma_{j}} \quad (14)$$

and total increment of strain is:

$$\mathrm{d}\varepsilon_{ij} = D^{-1} d\sigma_{j}^{e} + \lambda \frac{\partial f}{\partial \sigma_{j}} \quad (15)$$

Where, *D* is elastic matrix, $\mathrm{d}\sigma_{ij}^{e}$ is increment of elastic stress. The yield criteria of coal body can be described by using Drucker-Prager Law as follows (Zhou, Li, 2008) [6]:

$$f(I_1, \sqrt{J_2}) = \alpha I_1 + \sqrt{J_2} - K \quad (16)$$

Where, I_1 and J_2 are first invariant of principal stress, and second invariant of deviatoric stress, and *a*, *k* are constants related to the cohesion (*c*) and fraction angle (ϕ) of geo-material, which can be determined as:

$$\alpha = \frac{2\sin\phi}{\sqrt{3}(3-\sin\phi)} \quad \kappa = \frac{6c\cos\phi}{\sqrt{3}(3-\sin\phi)} \quad (17)$$

According to the strengthening criterion of Drucker-Prager Law:

$$\sigma_p = \sigma_p^0 + \frac{(\sigma_p^m - \sigma_p^o)\varepsilon^{ep}}{A + \varepsilon^{ep}} \quad (18)$$

Where, σ^o_p initial yield stress, MPa; σ^m_p is maximum value of reinforcement function, MPa; ε^{ep} is equivalent strain, and *A* is controlled constant of plastic hardening rate.

During **Model development and boundary conditions** the model development, there are several aspects are taken into consideration, including 1) dimension of model, 2) boundary conditions of model, 3) parameters assigned to the model, 4) dynamic impact loading.

First of all, considering possible influential range of high pressure gas impact loading detected from field work, the dimension of model is built with 20m x 20m x 30m as shown in Figure 4.

When the boundary conditions of the model are concerned, except for the symmetric face, non-reflecting boundaries were enforced to the other faces of the model to simulate the infinite rock mass, where no external loading is involved, and the top face of model is loaded uniformly distributed load, which is determined by the burial depth of coal seam (*γh*). In addition, the parameters obtained during the field work are assigned to the model as shown in Table 1.

Finally, for the impact loading, an uniformly distributed dynamic impact loading is applied on the borehole wall located at the middle of symmetric face of model with 0.5m in length, which is determined by the length of discharge tube of the highly pressurized carbon dioxide gas fracturing technique. The dynamic loading is defined by the relation of impact loading (*p*) and acting time (*t*), the detailed *p* - *t* relationship will be discussed in the following section.

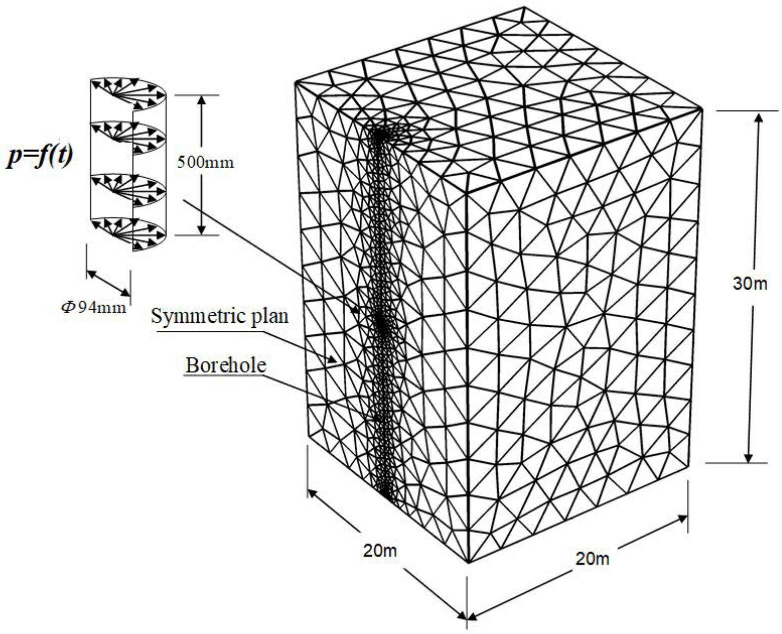


Figure 4: Model and mesh

Parameter of coal seam	Value	Unit
Modular of elasticity of coal containing gas	0.4	GPa
Volumetric modulus of coal containing gas	0.63	GPa
Shear modulus of coal containing gas	0.145	GPa
Poisson ratio	0.39	-
Density of coal body	1300	kg/m^3
Porosity	0.01	-
Permeability	0.00009	mD
Internal friction angle	30	degree
Cohesion	0.34	MPa
Protodyakonov coefficient (*f*)	0.5	-
Gas density	0.714	kg/m^3
Gas dynamic viscosity	1.00E-05	Pa•s
Original gas pressure	0.4	MPa

Table 1: Parameters assigned to model

The *p* - *t* relationship

Dynamic loading in current case is related to physical expansion. After discharge of the highly pressurized liquid carbon dioxide gas fracturing technique, the high pressure gas is released from the sealed compressed gas cylinder, then the pressure of gas reduces with time elapsed.

To simulate such dynamic impact loading, the relationship between the discharge pressure (p) generated by the highly pressurized liquid carbon dioxide gas fracturing technique and the duration of loading (t) applied on the borehole wall, in other words, the decay function of discharge pressure with time, must be determined. In there, there are two parameters involved, first, the maximum gas pressure applied on the borehole wall after discharge and second, the decay time of the gas pressure.

It is noted that the maximum discharge pressure generated by the system is 276MPa, which is the failure pressure of rupture disc. However, this pressure may be changed due to: 1) the geometry of discharge tube (head), 2) the numbers of nozzle installed on the discharge tube (head) and nozzle distribution pattern, and 3) the geometry of nozzle. Considering current research does not focus on these issues, for simplicity, the maximum pressure generated by the technique, 276MPa, is used in current numerical modeling.

From literature review, some decay functions, which were used to describe the blasting pressure and duration of loading in different types of media, have been found and these functions are summarized as follows:

Firstly, the pressure decay function in steel structure. To obtain the decay function, an experimental study was carried out on steel beam under blast loading. The experimentally measured blast waves were conventionally idealized by Eq(19), where P_+ is peak force in positive duration t_d, b is a shape parameter having major effects especially for the shape of negative phase (Figuli, et al, 2017) [7].

$$P(t) = P_+(1-\frac{t}{t_d})e^{-b\frac{t}{t_d}} \tag{19}$$

Figure 5a shows the pressure decay function of blast loaded on steel beam. Throughout the pressure-time profile, two main phases can be observed, including the positive phase of duration and the negative phase of duration. The negative phase is of a longer duration and a lower intensity than the positive duration.

Secondly, the pressure decay function in rock. Use of explosives is the most cost effective and widely used rock excavation method in coal mine, such as the drilling and blast. The damage induced by blasting is mainly results of explosive stress waves and subsequent explosive gas expansion.

The blast pressure loaded on the borehole wall can be determined as (Yanga, et al, 2007) [8]:

$$P_W = \frac{\rho_e V_d^{\ 2}}{2(\gamma+1)}(\frac{d_c}{d_b})^{2\lambda} \tag{20}$$

where ρ_e is the explosive density, V_d is the velocity of detonation, d_c is the change diameter, d_b is the blast hole diameter, d_b is the specific heat ratio, and γ is the explosive's adiabatic expansion constant, normally, $\lambda = 3$.

The borehole wall pressure-time history is adopted to approximate the borehole pressure-time history, which was proposed as (Yang, et al, 2017) [8]:

$$P_W(t) = 4P_W(e^{-\beta t/\sqrt{2}} - e^{-\sqrt{2}\beta t}) \tag{21}$$

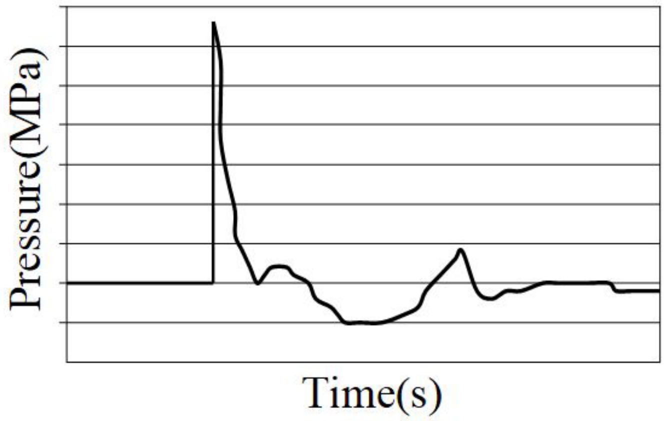
where, $P_w(t)$ is the borehole wall pressure-time history, t is time, P_w is borehole wall pressure, and β is a damping factor that is determined on the basis of rising time of borehole pressure to it peak. According to Eq.(21), the peak pressure occurs at $t_r = -\sqrt{2}\ln(1/2)/\beta$, so, the damping factor can be expressed as $\beta = -\sqrt{2}\ln(1/2)/t_r$. Figure 5b shows the borehole wall pressure-time history in rock material.

Thirdly, the pressure decay function in cellular material. Cellular materials, such as open and closed foams, honeycombs, and metal hollow spheres, are new classes of ultra-light multi-functional materials that can be withstand large deformation at nearly constant plateaus stress. These materials can absorb a large amount of kinetic energy before collapsing to a more stable configuration. Cellular materials are attached as sacrificial layers to protect structures, machines, and infrastructure against dynamic events (Liang, et al, 2017) [9].

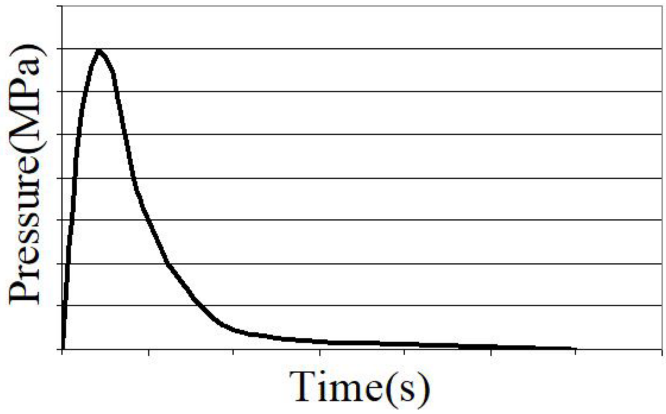
According to previous research work conducted, the linear decay function is proposed and used to describe the relationship between blast pressure and time in cellular material:

$$P(t) = P_0\left(1 - t/t_0\right) \tag{22}$$

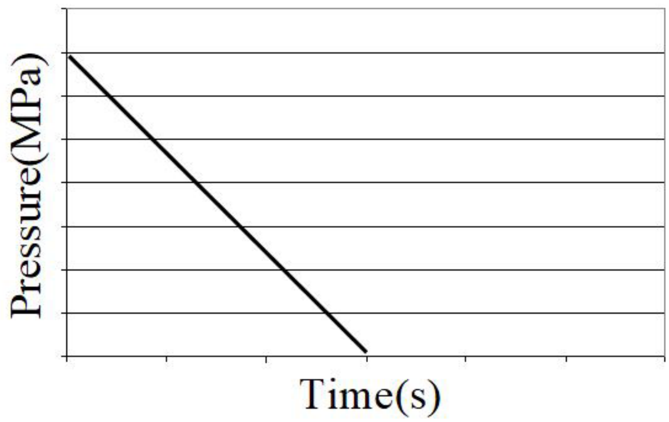
where, P_0 is peak force and t_0 is time duration and t is time, and Figure 5c depictures the relation between blasting pressure and time in graded cellular material.



a) Steal structure



b) Rock



c) Graded cellular material

Figure 5: Decaying paths in different types of media

Comparing three cases presented above, the decay function in rock is closer to current situation, so, Eq.(21) is adopted in the current modeling to define the relationship between pressure (P_w) and time (t), after discharge of highly pressurized carbon dioxide gas system. In other words, corresponding to time elapsed (t), the gas expansion pressure value (P_w) will be determined by Eq.(21). These two values are inputted into an interpolation function of COMSOL software, and act as dynamic loading on the borehole wall of coal seam based on the software algorithm.

Verification of numerical model

To make sure the numerical model developed can properly represent the reality of field conditions, the verification activity is carried out to identify and remove errors from the numerical model proposed, so that the correctness of the model is assessed and confirmed.

Previous research results indicated that: 1) a strong relationship exists between gas emission rates and stratigraphy and gas contents of coal seam, as well as the strengths of the overlying and underlying strata (Karacan, et al, 2011) [10], 2) the coal seam permeability depends on the coal lithology, cleat network and interconnection of pore spaces (Chatterjee and Pal, 2010) [11].

For a typical coal seam, the gas content, the strengths of overlying and underlying strata are constant, thus, above two statements imply that there is a strong relationship between the gas emission rate and the coal seam permeability. In other words, the gas drainage rate changes with the change of coal seam permeability.

Accordingly, the model verification and correctness assessment are conducted herein on the basis of comparing the variation of gas concentration monitored from the field work with the variation of coal seam permeability determined from the numerical modeling.

Figure 6 shows the comparison result. In here, *y* axis represents the values of coal seam permeability and gas concentration, and it also shows the location of fracturing borehole. With an increasing of the distance from a fracturing borehole, the coal seam permeability simulated from numerical model and the gas concentration monitored from three different locations on both sides of the fracturing borehole (2.5m, 7.5m and 10.5m) decrease.

It is noted that both variations present similar trend, which implies that the numerical model developed is consistent with the actual field conditions.

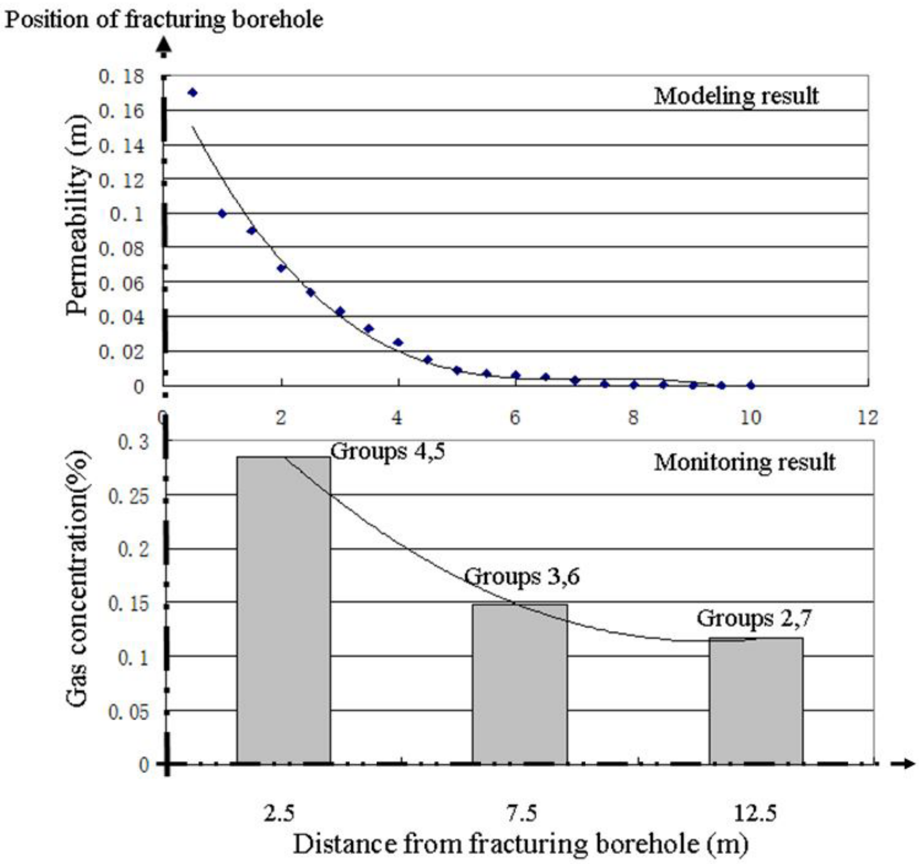


Figure 6: Variations of simulated permeability and monitored gas concentration

Modeling results and discussion

Based on the purposes of this study, the natural and operational factors affecting the coal seam fracture stimulation and improvement of coal seam gas drainage efficiency have been simulated numerically; the results are presented and discussed as follows.

Effect of natural factors on coal seam fracture stimulation and gas drainage improvement

It is noted that the coal seam fracture stimulation and the gas drainage improvement using the highly pressurized liquid carbon dioxide gas fracturing technique are related to the deformation and failure of borehole wall, the fracture formation within the coal seam and gas pressure gradient of coal seam, so, these parameters will be analyzed accordingly.

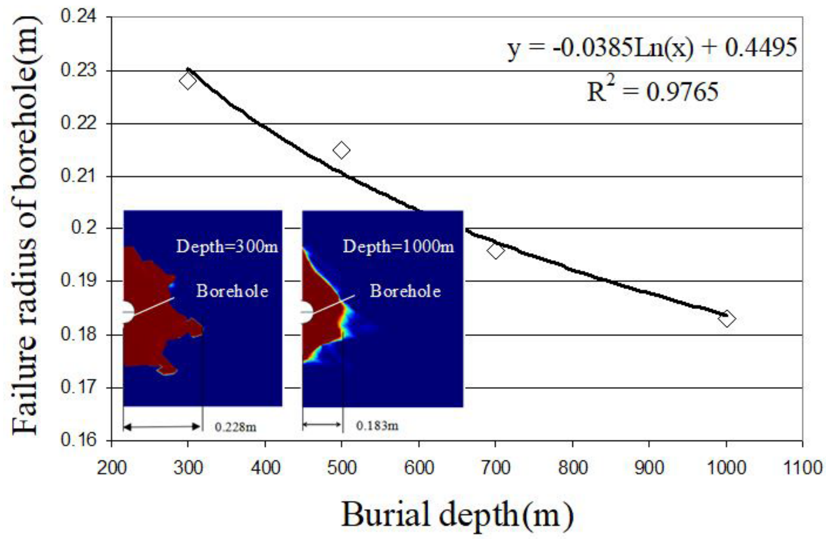
For coal seam fracture stimulation and gas drainage operations, there are many factors, such as the geological and geomechanical characteristics of coal seam, may be defined as the natural factor, but, in current study, the natural factors only involve the burial depth of coal seam and the coal body strength, which are considered to play an important role in coal seam fracture stimulation and gas drainage operations.

The burial depth of mineral resources like coal continuously increases due to the exhaustion of shallow resources, as the result, the ground stress increases accordingly. A common approach for determining the in-situ stress field is to assume that the pre-mining principal stresses are vertical and horizontal. Then, the vertical stress component can be estimated by the weight of the overburden, with σ_v=0.025-0.027 *h* (*h* is depth), even this assumption is not always true. The characteristics of high ground stress in deep ground inevitably affect fracture of rock blasting (Yang, et al, 2018) [12].

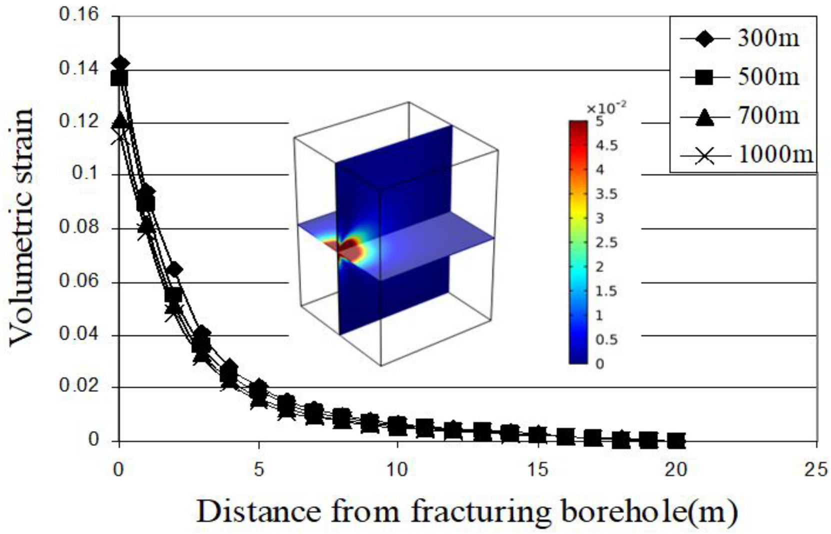
To understand the effect of burial depth on coal seam fracture stimulation using the highly pressurized carbon dioxide gas fracturing technique, four burial depths are selected to simulate their effect on the deformation and failure as well as the gas pressure gradient of the coal seam.

Figure 7a shows the plastic failure around borehole wall under the high pressure gas impact loading with different burial depths. The failure radius around borehole wall reduces with an increasing of burial depth, which presents a logarithmic relation. It implies that the failure and fracture propagation around borehole wall induced by the high pressure gas impact loading is restrained by the stress condition of coal seam.

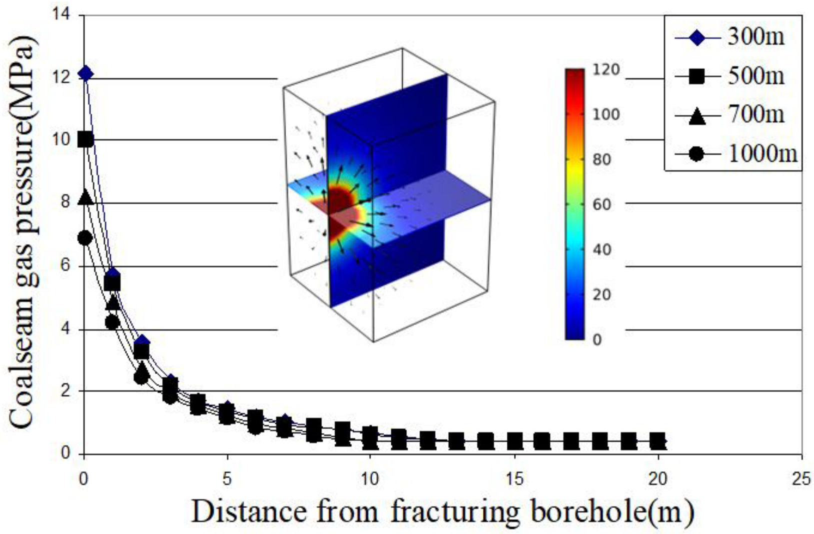
Figure 7b shows the volumetric strain distribution of the coal seam associated with various burial depths. It demonstrates the influence of buried depth on the volumetric strain of the coal seam is relatively limited, and it is also true for its effect on the gas pressure gradient within the coal seam (Figure 7c).



a) Failure radius with burial depths



b) Volumetric strain within coal seam with burial depths

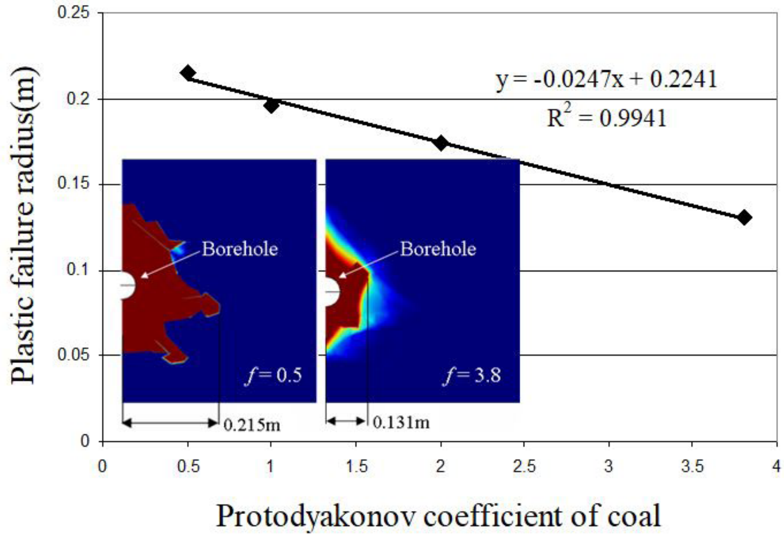


c) Gas pressure distribution of coal seam with burial depths

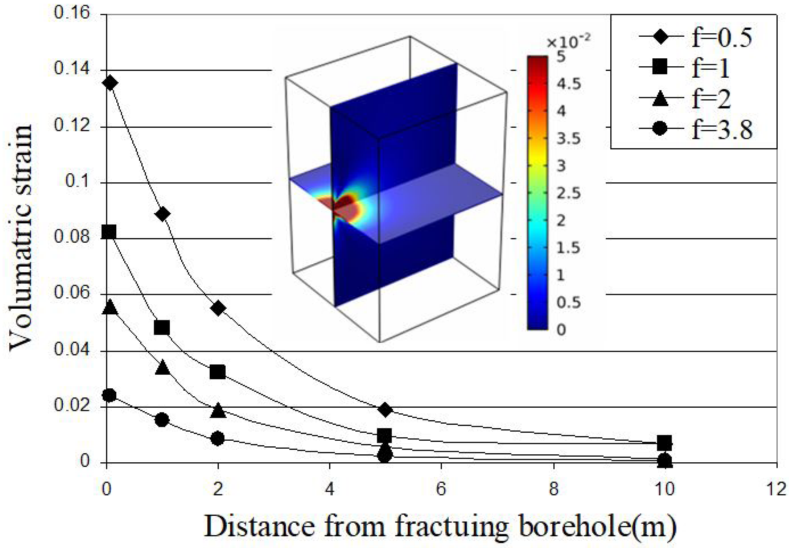
Figure 7: Effect of burial depth on failure, deformation and gas pressure of coal seam

On the other hand, it is recognized that the higher the strength of coal body, the smaller the fracture propagation of coal seam under the same loading condition. Thus, the strength of coal body, as another geomechanical parameter of coal seam, should be taken into consideration during the coal seam fracture stimulation and gas drainage operations.

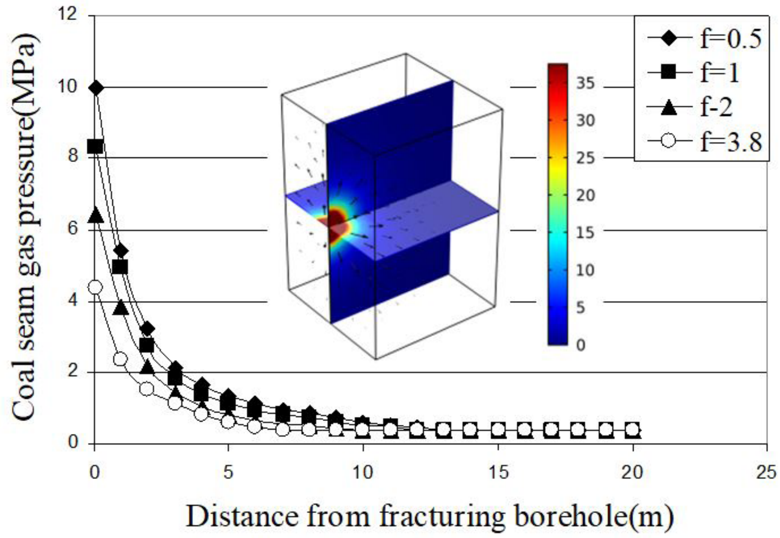
In current modeling, four levels of the Protodyakonov coefficient of coal body, including f = 0.5, 1, 2, 3.8, which represents low, moderate and high coal strength, are simulated respectively. The results are given in Figure 8.



a) Failure radius around borehole with coal strength



b) Coal seam deformation with coal strength



c) Gas pressure distribution of coal seam with coal strength

Figure 8: Effect of coal strength on deformation and failure

It is revealed from the modeling results, the failure radius around borehole wall reduces with an increasing of coal body strength linearly (Figure 8a), and corresponding to different coal strength, the internal deformation of coal seam varies significantly (Figure 8b), which implies that the coal strength have a significant impact on the fracture development and propagation of coal seam. For different coal strength, the gas pressure gradient built up in coal seam is obvious within 5m (Figure 8c). Overall, the modeling results are consistent with the traditional concept, that is, the coal strength may significantly influence the fracture development of coal seam during the coal seam fracture stimulation operation.

Comparing these two uncontrollable parameters, the coal strength is a more sensitive parameter, which may significantly affect the fracture formation and propagation during the coal seam fracture stimulating operation.

Effect of operational factors on coal seam fracture stimulation and gas drainage improvement

Of operational factors considered, the discharge pressure, the space between discharge heads, and number of discharge set used, are simulated to clarify how these factors influence the borehole wall failure, fracture formation of the coal seam and the gas pressure gradient built up within the coal seam.

Firstly, five levels of discharge pressure, which is the most important operational factor for the coal seam fracture stimulating operation, are selected to study its effect on coal seam deformation and failure around borehole wall.

Table 2 shows plastic failure around borehole wall associating with different discharge pressures. Obviously, the value of plastic failure radius varies logically with the different discharge pressure applied.

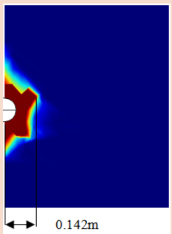
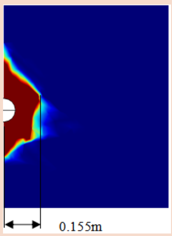
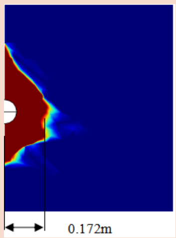
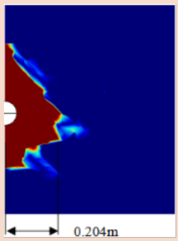
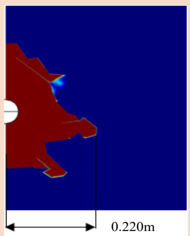
126MPa	140MPa	190MPa	236MPa	276MPa
				

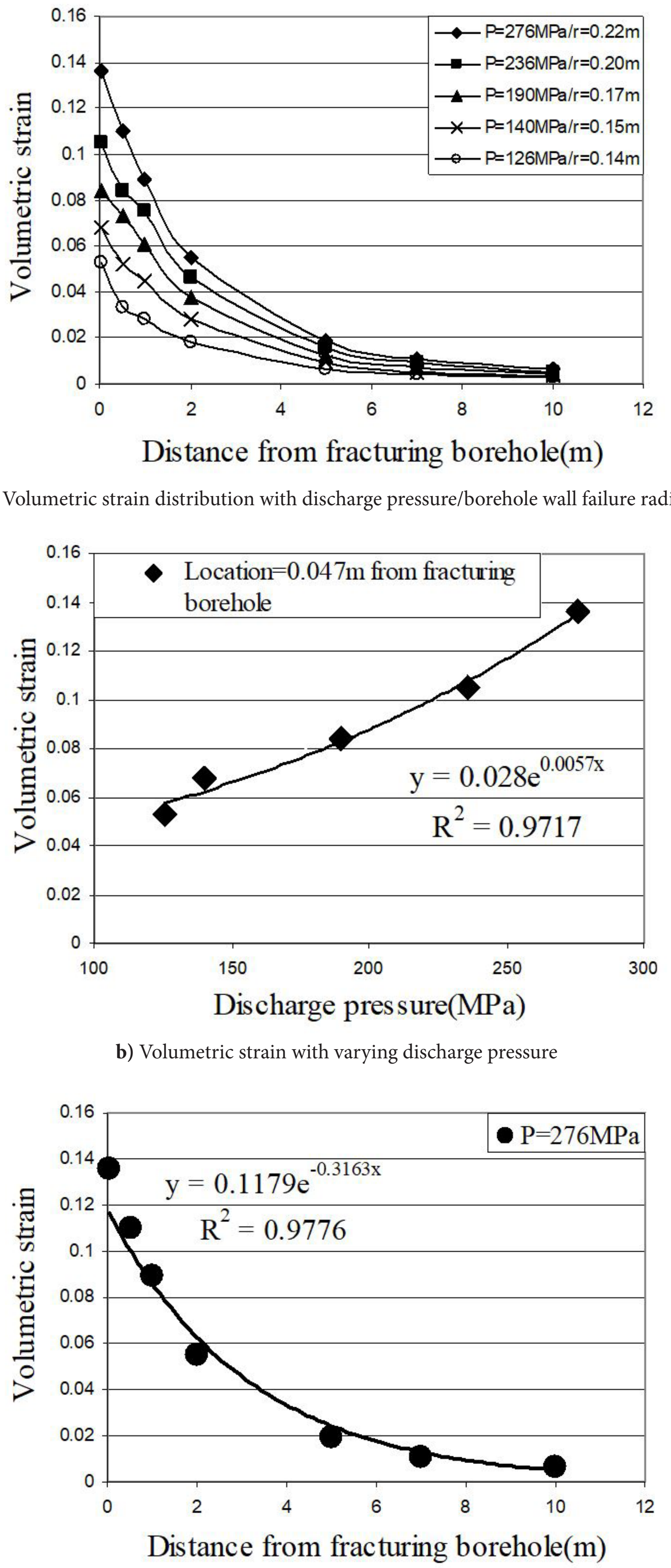
Table 2: Failure around borehole with different discharge pressures

Apart from plastic failure around borehole wall, the internal deformation and/or failure of coal seam induced by the high pressure gas impact loading may directly influence porosity structure and permeability of coal seam. Theoretically, the gas permeability of a coalbed is influenced during gas production not only by the simultaneous changes in effective stress and gas slippage, but also by the volumetric strain of the coal matrix that is associated with gas desorption (Harpalani and Chen, 1997) [13], as well as the degree of damage, which is related to the deformation of coal (Yang, et al, 2011) [14]. The relationship between permeability and volumetric strain is given as (Sun, et al, 2018) [15]:

$$K = k_0 \times \left(\frac{1 + \Delta\varepsilon}{n} \right)^2 \tag{23}$$

where, K is permeability, k_0 is initial permeability, n is porosity of media, and Δ is increment of volumetric strain.

In the light of above theoretical relationship, Figure 9 presents the relationships between the volumetric strain of coal seam and the discharge pressure applied (P)/failure radius(r)(Figure 9a), and the borehole wall deformation and the discharge pressure applied (Figure 9b), as well as the distribution of volumetric strain within the coal seam under the maximum gas impact loading(276MPa) (Figure 9c).



a) Volumetric strain distribution with discharge pressure/borehole wall failure radius

b) Volumetric strain with varying discharge pressure

c) Volumetric strain distribution within the coal seam

Figure 9: Volumetric strain of coal seam with discharge pressure applied

Based on Eq.(23) and the results obtained from Figure 9b, that is, the relationship between the permeability(K) of coal seam and the discharge pressure(P) generated by the highly pressurized carbon dioxide gas fracturing technique can be proposed as:

$$K = k_0 \times \left(\frac{1 + 0.028e^{0.0057P}}{n} \right)^2 \tag{24}$$

Also, the distribution of coal seam permeability under the maximum discharge pressure, 276MPa, can be determined as:

$$K = k_0 \times \left(\frac{1 + 0.12e^{-0.3x}}{n} \right)^2 \tag{25}$$

where, x is a distance from fracturing borehole, m.

On the other hand, In order to improve the gas drainage efficiency of coal seam, apart from coal seam permeability, the gas pressure gradient of coal seam is another important factor, which is a driving force to make the gas moves from the fracturing borehole to the drainage boreholes within the coal seam.

Considering the features of the highly pressurized liquid CO_2 fracturing technique, it generates not only the high pressure gas impact loading, but also, a certain amount of expansive gas, thus, after discharge of the technique, the high pressure gas impact loading is applied on the borehole wall, and it causes significant deformation/failure of coal seam, and at same time, forms the local high pressure gas zone around the fracturing borehole. Accordingly, the gas pressure gradient of coal seam is built up. Figure 10 gives the gas pressure distribution within the coal seam under the maximum gas impact loading.

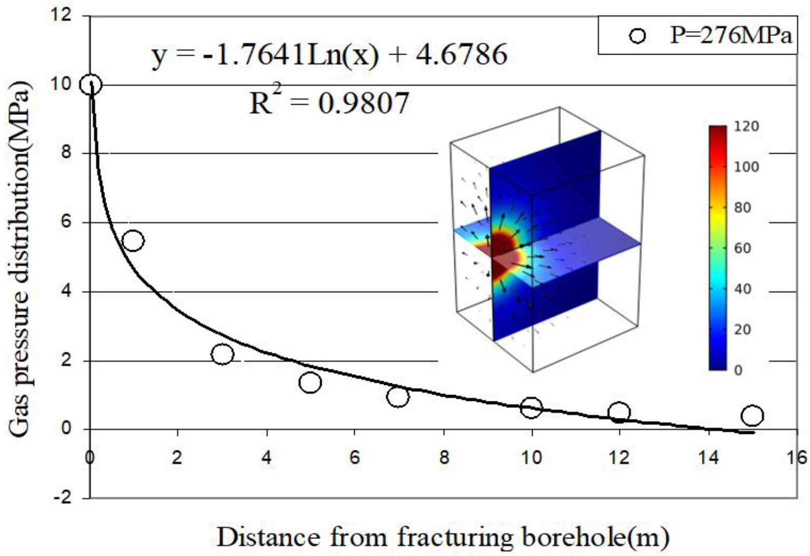


Figure 10: Gas pressure distribution of coal seam under high pressure gas impact loading

According to Darcy flow theory, owing to discharge pressure causes a rise of pore-pressure of coal seam around fracturing borehole, and the flow of coal seam gas to the drainage borehole takes place through the fractural network. As a result, an increment of gas concentration/flow can be detected.

Theoretically, the coal seam gas density(ρ_g) can be expressed as (Liu, et al, 2017) [16]:

$$\rho_g = \frac{M_c}{RT} p \tag{26}$$

where, M_c is molar mass of methane, kg/mol, p is gas pressure of coal, MPa, R is universal gas constant, J/(mol·k), T is temperature of coal, K.

Based on the gas pressure distribution of coal seam determined from Figure 10, the gas density at different location within the coal seam (under the maximum discharge pressure, 276MPa) can be determined:

$$\rho_g = \frac{M_c}{RT}(-1.8Ln(x)+4.8) \tag{27}$$

where x is distance from fracturing borehole, m.

During the coal seam fracture stimulating operation, it is very common to have different thickness of coal seams. When thick coal seam is encountered, the multi-discharge technique (system) must be selected. For the multi-discharge system, there is a space between the discharge sets. During the field operation, it is observed that the effective gas drainage radius does not change significantly with an increasing of number of discharge set used. One of the reasons caused is due to the space between two discharge heads, which prevents accumulation of energy generated by two adjacent discharge heads.

However, if the space is small enough, can energy generated by adjacent discharge sets be accumulated, and if yes, can effective drainage radius be increased? To answer these questions, the different spaces between two discharge heads varying from 1-5m (under 276MPa) are simulated respectively.

According to the modeling results, one meter space gives the best outcome comparing with others, and it seems to have some impact on the effective gas drainage radius (Figure 11). However, looking at the variation of drainage radius in y-axis, the incremental percentage of drainage radius varies from 5.9% to 1.5% with different spaces selected, which clearly indicates that the influence of this parameter to the effective gas drainage radius is very limited.

On the other hand, from manufacturing point of view, it is possible to further reduce the space between two discharge sets by shortening the length of CO_2 storage (tube), but, the quantity of liquid CO_2 will be compromised. Therefore, it is unnecessary to take serious consideration about this issue.

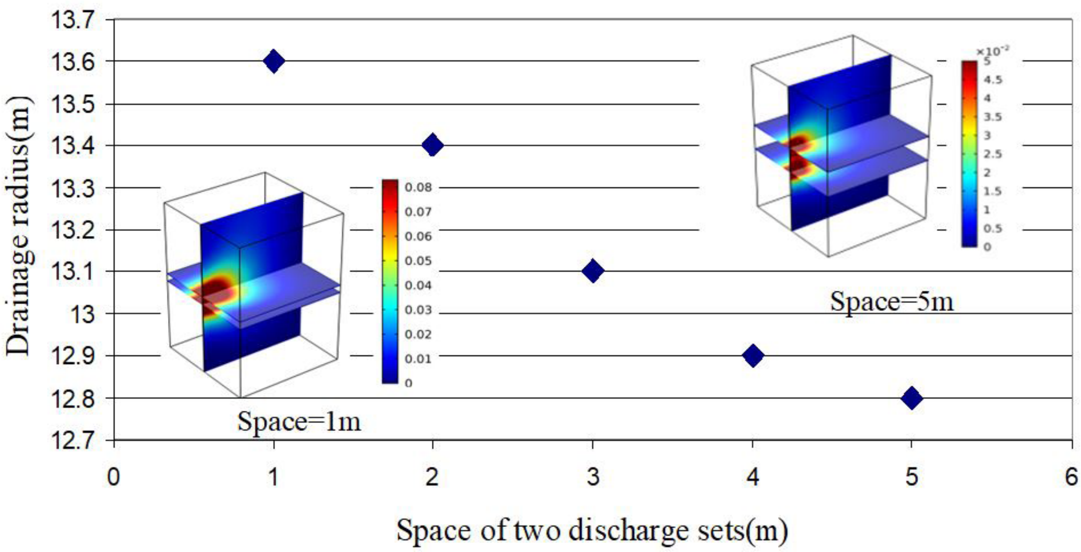


Figure 11: Effect of space between two discharge heads on coal seam deformation

Following above results obtained, one meter, which is recognized as the best space, is used to simulate the effect of different numbers of discharge set (head) on coal seam deformation, failure and gas pressure distribution.

The result demonstrated the effect of five different discharge sets on the internal coal seam deformation (Figure 12). It reveals the internal deformation characteristics of coal seam with different numbers of discharge set used, and it shows that, within five meters from the fracturing borehole, different numbers of discharge set has significant impact on the deformation/permeability of coal seam, over five meters, the impact decreases gradually, and no impact can be found after ten meters, regardless of numbers of discharge set used. These modeling results give the similar conclusion as the results observed from field work, that is, the gas drainage radius will not increase significantly with increasing number of discharge set used.

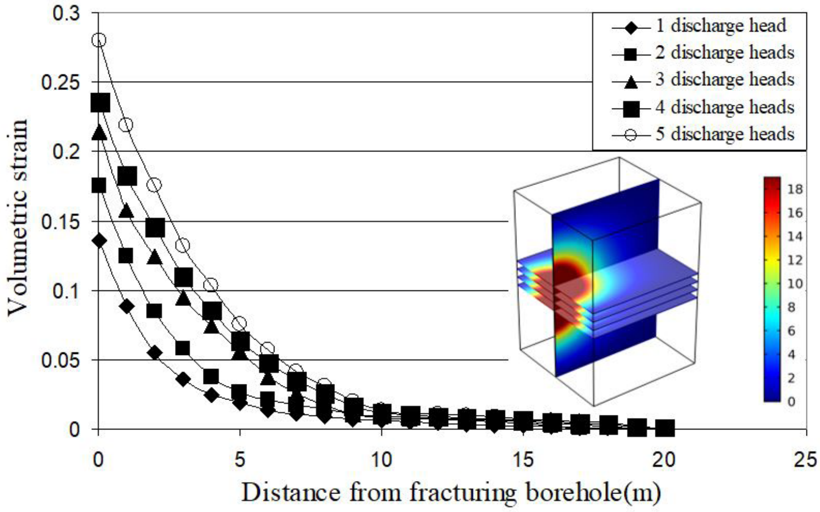


Figure 12: Number of discharge set with volumetric strain of coal seam

Gas permeability associated with volumetric strain of coal seam

When the coal seam is applied the external force, in current case, the highly pressurized gas impact loading, the significant variation of volumetric strain of coal seam occurs, which may lead to change of porosity and permeability of coal seam. The theoretical formula between the volumetric strain and the permeability, has been proposed as (Ran et al,1997) [17]:

$$\varphi = 1 - \frac{1-\varphi_0}{1-\varepsilon_V} = \frac{\varphi_0 - \varepsilon_V}{1-\varepsilon_V} \tag{28}$$

where, φ_0 is the initial porosity, ε_V is the volumetric strain, which can be expressed as

$$\varepsilon_V = \frac{\Delta V_b}{V_b} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$$

and V_b is the bulk volume, ΔV_b is the increment in the bulk volume, and ε_{11}, ε_{22}, ε_{33} are the principle strains; is the bulk unit weight.

According to the Eq.(28), it suggested that if the rocks are in a compressive state and the cracks tend to close, the volumetric strain will decrease, and consequently, the porosity and permeability of the rocks will decrease. In contrast, if the rocks are in a dilatancy state and the cracks propagate, the volumetric strain will increase, thus increasing the porosity and the permeability of the rocks. Therefore, the porosity and the permeability of rocks are expected to change with the variation in the volumetric strain (Wu et al, 2020) [18].

Gas desorption associated with variation of volumetric strain of coal seam

The gas permeability of a coalbed is influenced during gas production not only by the simultaneous changes in effective stress and gas slippage, but also by the volumetric strain of the coal matrix that is associated with gas desorption. The relationship between the volumetric strain with the amount of gas desorbed from coal has been established as (Harpalani, Chen, 1997) [13]:

$$\frac{\Delta V_m}{V_m} = \beta V_{des} \tag{29}$$

where, ΔV_m is incremental matrix volume of coal, m^3, V_m is original matrix volume of coal, m^3, β is a constant depending on the characteristics of the coal type, V_{des} is the volume of gas desorbed, which can be represented by Langmuir's equation.

Previous research indicated that over 95% of the gas is stored in the coal matrix as adsorbed gas (Gray, 1987) [19]. According to the theoretical relationship given in Eq.(29) and the modeling results - the volumetric strain variation of coal seam associated with the highly pressurized gas impact loading, obtained from the current study, it is expected that more free gas adsorbed on coal matrix can be released under the high pressure gas impact loading and it can be drained effectively with the fracture network developed and the gas pressure gradient built up within the coal seam.

Effect of high pressure gas impact loading on improvement of gas drainage efficiency

When coal seam is subjected to the highly pressurized gas impact loading generated by the liquid CO_2 fracturing technique, following changes may occur and result in improvement of coal seam gas drainage efficiency as:

Firstly, the plastic failure occurs around the borehole wall of fracturing borehole, which is induced directly by the dynamic impact loading. Theoretically, when the borehole is subjected to radial compression, in current case, the highly pressurized gas impact loading, the radial displacement takes place around the borehole wall, and it causes the tangential tensile strain within the coal body, so, the radial fractures and failure occurred as shown in Table 2. During the unloading, the radial stress around the borehole wall changes from the compressive stress to the tensile stress, which leads to the formation of circumferential fractures around the borehole.

Then, due to highly pressurized gas impact loading, a significant variation of internal structure of coal seam occurred. The evidences are provided by the variation of volumetric strain within the coal seam. It implies that the fracture network of the coal seam has been propagated further. On the other hand, as the significant variation of volumetric strain of coal seam may lead to change of porosity and permeability of coal seam, so the improvement of coal seam permeability are expected.

In addition to improvement of coal seam porosity or permeability mentioned above, it is noted that the gas desorbtion from coal is proportional to the volumetric strain occurred within the coal seam, as the result, the gas adsorbed in coal body may be released, so the efficiency of coal seam gas drainage can be improved.

Finally, after application of the highly pressurized liquid carbon dioxide fracturing technique, a relatively large volume of gas is generated due to liquid carbon dioxide phase transition in the borehole, the highly pressurized gas penetrates into the existing fractures of coal seam, and the fracture network of coal seam is dredged and expanded.

Also, due to sudden increasing of local gas pressure (around fracturing borehole), the gas pressure gradient in the coal seam is formed, which is a driving force to mobilize the gas movement within the coal seam.

In summary, the numerical simulation results show that the highly pressurized liquid carbon dioxide fracturing technique provides following fundamental functions in improving efficiency of coal seam gas drainage: 1) improving coal seam porosity/ permeability and 2) releasing gas adsorbed from coal seam, 3) forming gas pressure gradient of coal seam. Among them, the first function develops/stimulates the coal seam fracture network, the second function releases more free gas for drainage and the third function, as the driving force, mobilizes the gas released from the fracturing borehole to the drainage boreholes through the network developed/stimulated [20,21].

Conclusions

Practical experiences indicated that the continued use of traditional underground gas drainage method alone will not be capable of draining sufficient gas in the relatively short time to support high production rates by longwall mining in gassy and low permeability conditions. Thus, new coal seam fracture stimulation technology has been constantly developed and applied to coal mines for gas control and management, the highly pressurized liquid carbon dioxide fracturing technique is one of them, which is utilized to stimulate coal seam fracture and improve coal seam gas drainage efficiency.

During the field applications, it is realized that there are many factors, such as, natural and operational factors, may change the outcomes of coal seam fracture stimulation and coal seam gas drainage performance, and these factors are difficult to be studied individually in the field work. So, the multiphysics coupled modeling has been carried out to gain insight into the effect of natural and operational factors on the results of coal seam fracture stimulation and performance of coal seam gas drainage. According to numerical simulation, the following results can be drawn as:

1) When the natural factors have been concerned, two factors, including the burial depth and the coal strength, have been studied.

• It is revealed that the failure radius around borehole wall reduces with an increasing of the burial depth as a logarithmic function. It implies that the failure and fracture propagation around borehole wall induced by the high pressure gas impact loading is restrained by the stress condition of coal seam. But, there is no significant influence found on the internal fracture propogation and the gas pressure distribution of coal seam.

• Similarly, the failure radius around borehole wall reduces with an increasing of the coal strength linearly, and the internal deformation of coal seam varies obviously with the coal strength, which indicates that the coal strength have a significant impact on the internal fracture development and propagation of coal seam, and it is also true for the coal seam gas pressure distribution, particularly within the 5m from the fracturing borehole.

2) For the operational factors, three factors, including, the discharge pressure, the space between two discharge sets, and number of discharge set used, are simulated.

Firstly, for the different discharge pressure applied to the coal seam, it is found that:

• The failure radius around the borehole wall varies logically with the different discharge pressure applied, that is, the failure radius is proportional to the highly pressurized gas impact loading applied.

• Apart from failure radius around borehole wall, the internal deformation and/or failure of coal seam induced by the high pressure gas impact loading have changed the porosity structure and improved the permeability of coal seam. The volumetric strain within the coal seam induced by the different gas impact loadings has provided the evidence to support this statement.

• On the basis of the volumetric strain distribution within the coal seam under the maximum discharge pressure, a mathematical formula has been proposed to calculate the permeability of coal seam within the affected region (Eq.25).

• Similarly, according to the gas pressure distribution of coal seam, a numerical equation(Eq.27) proposed enables one to precisely calculate the gas density at different position within the coal seam.

Secondly, the factors related to the multi-discharge system have been simulated, including space between discharge sets, and number of discharge set used, the results indicated that:

• One meter space (between two discharge sets) gives the best result comparing with others. Reducing the space seems to have some impact on the effective gas drainage radius. However, comparing the different spaces between two discharge sets selected, the incremental percentage of the drainage radius varies from 5.9% to 1.5%, which clearly indicates that the influence of this parameter is very limited.

• From manufacturing point of view, it is possible to further reduce the space between two discharge sets by shortening the length of CO2 storage (tube), but, the quantity of liquid CO2 will be compromised. Obviously, it is unnecessary to take serious consideration about this issue.

• When numbers of discharges set is taken into consideration, 1 to 5 discharge sets have been selected during the modeling, and it shows that, within five meters from the fracturing borehole, the numbers of discharge set has significant impact on the deformation/permeability of coal seam, over five meters, the impact decreases gradually, and almost no impact can be found after ten meters, regardless of numbers of discharge set used. This modeling result gives a similar conclusion as that observed during the field work, that is, the gas drainage radius will not increase significantly with increasing number of discharge set used.

When coal seam is subjected to the high pressure gas impact loading, the variation of coal seam takes place as:

• The plastic failure occurred around the borehole wall induced directly by the highly pressurized gas impact loading.

• Due to discharge vibration and/or stress wave, a significant variation of internal structure of coal seam occurred, which implies that the fracture network of the coal seam was developed further.

• The volumetric strain occurred in coal seam may cause coal seam relaxation, and the adsorption pressure in coal seam is reduced, so the gas adsorbed in the coal body can be released.

• The highly pressurized gas, generated by the technique, penetrates into the existing coal seam fractures, and the fracture network of coal seam is dredged and expanded, also due to sudden increase of local gas pressure (around fracturing borehole), the gas pressure gradient in the coal seam is formed, which is a driving force to mobilize the coal seam gas movement.

• The highly pressurized liquid carbon dioxide gas fracturing technique utilizes three mechanisms to improve coal seam gas drainage efficiency, including, 1) improving the coal seam permeability, 2) causing coal seam relaxation and releasing gas adsorbed in coal body 3)forming gas pressure gradient within the coal seam. The first one develops/stimulates fracture network of coal seam, and the second one makes more free gas ready to move, and the third one, as a driving force, mobilizes the free gas released from the fracturing borehole to the drainage boreholes through the network developed/stimulated.

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