Crack initiation and propagation in coalbed gas reservoir during hydraulic fracturing

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Abstract. The crack initiation and propagation calculation model during hydraulic fracturing in a coalbed methane reservoir with interlayers is established in this paper. The influence of coal elasticity modulus and fracturing fluid displacement on the fracture geometry are studied. Results show that the fracture initiation begins at the perforation interval. Stress inhomogeneity is detrimental for the formation of multiple cracks for the extension of the fracturing area. The cracks at the boundary have changed from less developed to more developed with increasing horizontal stress coefficient. The coal elasticity modulus and fracturing fluid displacement both play a determinative effect on fracture geometry. The study provides a reference basis for implementing hydraulic fracturing of low permeability coal seams with interlayers.

Keywords. Crack; coalbed gas reservoir; interlayer; stress concentration; numerical analysis.

1. Introduction

Coalbed methane (CBM), as a kind of self-generated and self-storage unconventional gas in coal seam, is a very important clean energy [1, 2]. The vigorous development of CBM resources can improve energy utilization efficiency, reduce the dependence on imported oil and gas, and reduce the environmental pressure caused by coal burning [3, 4]. However, the low matrix permeability of coalbed methane reservoir makes it difficult to have natural capacity. So it must rely on the hydraulic fracturing to increase the production to obtain a better capacity [5, 6]. The characteristics of physical and mechanical properties on coal rock, the distribution conditions of interlayer, and the construction parameter all have great influence on the hydraulic fracturing effect [7, 8]. Therefore, it is an urgent problem for the academic and engineering experts to study the complex fracture initiation and propagation rule of hydraulic fracturing in coalbed methane reservoir. Many studies on

theory and experiment have been carried out to investigate the characteristics of hydraulic fracture initiation and propagation in CBM reservoirs.

Sobhaniragh [9] presented a poro-elasto-plastic computational model for 2-D hydraulic fracture propagation simulation. They found that the design of the fracture spacing of the first two fractures is of highly importance so as to ensure adequate degree of interference without the concern of generating so much induced stress. Pakzad [10] proposed that the hydraulic fractures propagated perpendicular to the minimum principal far-field stress direction for high-permeability models under anisotropic far-field stress conditions. Jiang and Zhang *et al* [11] built a geological-geomechanical model to study the effects of bedding on the fracture propagations during hydraulic fracturing. The effects of injection pressure, well completion method, in-situ stress difference coefficient, and fracturing fluid displacement on the fracture propagations are investigated. Do [12] studied the fracture initiation pressure of a horizontal wellbore drilled in an anisotropic poroelastic medium. Then they analyzed the influence of Young's

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modulus ratio, permeability ratio, in-situ stress, bedding dip angle and anisotropic tensile strength on the fracture initiation pressure. Chuprakov [13] revealed the mechanical mechanism of the intersection of natural fractures and hydraulic fractures, and pointed out that the main control parameters were the ground stress difference, net pressure inside the cracks, and the friction coefficient and intersection angle of natural fracture surfaces. Hossain [14] established a generic model for predicting hydraulic fracture initiation and discussed the effects of fracture initiation causes on fracture propagation pressure and fracture volume. Based on the study of Jiang [15], elasticity modulus and fracture toughness difference between coal and bedding affect hydraulic fracturing propagation were presented. They proposed that a larger injection rate enhances the fracture size and the complexity of the fracture network. Yun [16] suggested a three-dimensional, dual-porosity, two-phase, pseudo-steady, non-equilibrium sorption mathematical model from desorption to flow by the help of petroleum reservoir numerical simulation method and this complex mathematical model is approximated and solved by finite-difference and fully implicit method.

In order to analyze the initiation and propagation characteristics of hydraulic fractures, an initiation and propagation model of hydraulic fractures in a CBM reservoir was built in the paper. At the same time, the effect of geological and construction parameters on the hydraulic fracture geometry were also studied. The model was used to analyse the influence of coal elasticity modulus and fracturing fluid displacement on the fracture geometry. The affects of interlayers in the coal seam on the fracture propagation are analyzed. Research results provide a reference basis for implementing the hydraulic fracturing of low-permeability coal seam and optimizing hydraulic fracturing parameters.

2. The initiation and propagation model of hydraulic fracturing

The fracturing fluid flow in a hydraulic fracture is laminar on account of the small fracture width in contrast to its length and height. Therefore, the fluid velocity along the fracture width can be considered to be zero and the disregard of the fracturing fluid flow along fracture width is very large. The following assumptions are made: (1) the fracturing fluid is Newtonian fluid; (2) the hydraulic fracture is elliptic; (3) the fracture height is the coal seam thickness. Based on Navier–Stokes equations [17, 18], the flow equations of are shown as below:

$$u_x = \frac{y^2}{2\mu} \frac{\partial p}{\partial x} + c_1 x + c_2 \quad (1)$$

$$u_z = \frac{y^2}{2\mu} \frac{\partial p}{\partial z} + c_3 z + c_4 \quad (2)$$

where u_x and u_z are the flow rates along x and z directions, respectively, m/s; μ is the viscosity of fracturing fluid, Pa·s; c_1, c_2, c_3, c_4 are boundary coefficients.

The boundary conditions are

$$u_x|_{y=\pm\frac{w}{2}} = 0 \quad (3)$$

$$u_z|_{y=\pm\frac{w}{2}} = 0 \quad (4)$$

$$c_1 = 0, \quad c_2 = -\frac{1}{2\mu} \frac{\partial p}{\partial x} \left(\frac{w}{2}\right)^2 \quad (5)$$

$$c_3 = 0, \quad c_4 = -\frac{1}{2\mu} \frac{\partial p}{\partial z} \left(\frac{w}{2}\right)^2 \quad (6)$$

where w is the fracture width, m.

The volume flow rate per unit length along the x direction is

$$q_x = \int_{-\frac{w}{2}}^{\frac{w}{2}} u_x dy = \int_{-\frac{w}{2}}^{\frac{w}{2}} \frac{1}{2\mu} \left(y^2 - \frac{w^2}{4}\right) \frac{\partial p}{\partial x} dy = -\frac{w^3}{12\mu} \frac{\partial p}{\partial x} \quad (7)$$

The pressure drop equation along the X direction is

$$\frac{\partial p}{\partial x} = -\frac{12\mu q_x}{w^3} = -\frac{12\mu q}{h_f w^3} \quad (8)$$

where q is the fracturing fluid flow at one side, $q=q_i/2$, m/s; q_i is fracturing fluid displacement, m/s; h_f stands for the maximum fracture height, m.

The fracture width at the distance x m from O can be written as:

$$w = w_0 \sqrt{1 - x^2/L^2} \quad (9)$$

where w_0 is the maximum fracture width, m; L is the half-fracture length, m.

Taking Eq. (9) into Eq. (8) and integrating, we obtain:

$$p = -\frac{12\mu q L x}{h_f w_0^3 \sqrt{L^2 - x^2}} + C_0 \quad (10)$$

where p is the pressure distribution in the hydraulic fracture plane, Pa.

The boundary condition is

$$p|_{x=0} = p_0 \quad (11)$$

where p_0 is the initial injection pressure of fracturing fluid at crack section, Pa.

Equation (10) can be changed into:

$$p = -\frac{12\mu q x}{h_f w_0^3 w} + p_0 \quad (12)$$

Known from Eq. (12), $w \rightarrow 0$ and $p \rightarrow -\infty$ when $x \rightarrow L$. The area is called the fluid lag area and the pressure is unreasonable because of the equation singularity. We assume that the fluid pressure in the lag area is not less than

the normal closure pressure of the fracture plane. Equation (12) can be changed into:

$$\begin{cases} p = -\frac{12\mu qx}{h_f w_0^2 w} + p_0, & p > \sigma_n \\ p = \sigma_n, & p < \sigma_n \end{cases} \quad (13)$$

where σ_n is the normal closure pressure of the fracture plane, Pa.

The fracture tip force diagram during hydraulic fracturing is shown in figure 1. The stress state of the fracture tip should satisfy the following equation:

$$\sigma_{teff} = \sigma_{H,min} - P_{frac} \quad (14)$$

where σ_{teff} is the effective stress of new fracture tip, Pa; $\sigma_{H,min}$ is the minimum horizontal principal stress, Pa; P_{frac} is hydraulic fracturing pressure, Pa.

At the cracking critical state, the crack tip has

$$\sigma_{teff} \geq \sigma_t \quad (15)$$

where σ_t is coal tensile strength, Pa.

When the spreading crack meets the natural fracture, the propagation direction may swerve and the fluid will flow into the natural fracture [19].

$$p_i = P_{frac} - \Delta p > \sigma_n + \sigma_t \quad (16)$$

where Δp is the pressure drop of the fracturing fluid along the hydraulic fracture, Pa; σ_n is the positive stress at the crack tip, Pa.

$$\sigma_n = \frac{\sigma_{H,max} + \sigma_{H,min}}{2} + \frac{\sigma_{H,max} - \sigma_{H,min}}{2} \cos 2(90^\circ - \theta) \quad (17)$$

where $\sigma_{H,max}$ is the maximum horizontal in situ stress, Pa; $\sigma_{H,min}$ is the minimum horizontal in situ stress, Pa; θ is the

included angle between hydraulic fracture and natural fracture, °.

3. Simulation and analysis

ANSYS software is one of the mainstream software in numerical simulation, which is used to build the stress and deformation calculation model of surrounding rock near the borehole as can be seen in the paper. Meanwhile, the algorithmic processor description language (APDL) is used to solve the command stream to describe the hydraulic fracture propagation in a low-permeability coal seam with interlayers. Based on the above operation, the automatic running of the program is realized and the operation efficiency is greatly improved. The numerical model of fracture initiation and propagation is established based on the geological parameters of Qinshui basin in Shanxi province. The geological parameters and other parameters used in the numerical simulation are shown in tables 1 and 2.

Based on the geological distribution characteristics of the target coal seam in Qinshui basin, the two-dimensional mechanical model of fracture propagation pattern is shown in figure 2. The calculation model is symmetric along the borewell axis with both the height and half-length of 400 m. In the model, the thicknesses of coal seam, overlying layer and substratum are 40 m, 180 m and 180 m, respectively. There are two interlayers marked red in figure 2, which divide the coal seam into three pieces of the same thickness. The full constraint displacement boundary condition is adopted at the bottom of the model. The horizontal displacement constraint is imposed on the four vertical boundaries to limit the horizontal displacement deformation. The free seepage boundary conditions are imposed on both sides and the bottom. Furthermore, the hydraulic pressure applied to the coal seam is the pressure value used in the numerical simulation. Because the calculation model

Figure 1. Crack tip stress diagram.

is of good symmetry, half of the model is set into calculation to improve the computational efficiency. The calculation model has 2654 nodes, 3466 elements and the element has three types: triangle, quadrilateral and hexagon. During numerical simulation calculation, the maximum unbalanced force and the convergence precisions are set as 50 N and 10^{-5} , respectively. The numerical simulation calculation has good convergence, and the calculation results of monitoring points became stable with increasing computing time steps.

The horizontal stress coefficient K is set as 1:1, 1.1:1 and 1.2:1 respectively when the other parameters are constant to study the effect of in-situ stress difference on the fracture propagation pattern. The initial pressure values are shown in table 3 and it decreases with the increase of K .

Figures 3–5 show the crack propagation rules at different fracturing fluid injection times in heterogeneous coal seam. From figures, the damage zone occurs at the perforation section firstly. The crack extends away from the wellbore gradually, and the fracture number increases to form a

Table 1. Geological parameters.

Lithology	E/GPa	ν	$\psi/^\circ$	C_0/MPa	T_0/MPa	$k(\text{m/s})$	e
Coal seam	3.7	0.25	20	64.9	8.6	10^{-9}	0.20
Overlying strata	5	0.30	15	44.9	8.4	10^{-10}	0.25
Substratum	5	0.30	15	44.9	8.4	10^{-10}	0.25
Interlayer	19	0.31	17	54.3	9.2	4.2×10^{-10}	0.28

where E is elasticity modulus, Pa; ν is Poisson's ratio; ψ stands for dilation angle, $^\circ$; C_0 is the initial compression yield strength, Pa; T_0 is the initial tensile yield strength, Pa; k is hydraulic conductivity, m/s; e is porosity.

Table 2. Other parameters in the numerical simulation.

Parameter	Value	Parameter	Value
Overburden pressure/MPa	15.92	Pressure gradient of overburden pressure/(MPa/100m)	2.65
Fracturing fluid displacement/(m^3/min)	4	Fracturing fluid density/(kg/m^3)	1300
Fracturing fluid viscosity/ $\text{mPa}\cdot\text{s}$	3	Pore pressure at coal seam top/MPa	5.88
Pore pressure gradient in coal seam/(MPa/100m)	1.0	Maximum horizontal principal stress/MPa	17.65
Coal rock tensile strength/MPa	1.4	Thickness of coal seam/m	40
Thickness of interlayer/m	1

Figure 2. Crack initiation and propagation model.

fracture network finally. In figure 3, the stress concentration appears on the wall of the well with the increase of the borewell pressure. When the stress greater than the tensile strength of coal rock, the fracture cracks and the micro-cracks occur at the top and bottom of the wellbore edge. The branch fractures will occur at the tip of the major crack with the increase of the wellbore pressure and the length of the branch fractures are increasing (figure 3(b)–(d)). The cracks can continue to propagate without any added stresses when the pressure in the wellbore increases bigger than the critical pressure of fracture instability. The tip of the major crack produces multiple irregular cracks, the number and the size of cracks increases greatly with injection time. The secondary fractures make the crack propagation path more complicated. The fracture will stop cracking when the crack expands to a certain extent, then we need to increase the wellbore pressure to make the cracks extend again.

From figures 3–5, the distribution of pore pressure in coal seam is uniformly at the initial stage of hydraulic fracturing. The fractures distribute symmetrically along the middle point of the perforation section. As the injection time of fracturing fluid increases, the pore pressure distribution is more and more significantly affected by the crack expansion, and the fracture asymmetry becomes more and more obvious. Furthermore, the asymmetry is obvious by the increase of the horizontal stress coefficient K . This is mainly because the fluid flows preferentially along these micro-fractures, eventually leading to the increase of pore pressure and further promoting the growth of micro-fractures. As a result of the existence of the interlayers, water

pressure cracks appear to cross layer phenomenon. The hydraulic fracturing fracture is dissected by the interlayers. When the horizontal stress coefficient is 1.0, the hydraulic fracture extends forward with the middle line of the perforation section as the symmetry axis. The number and size of secondary fractures increase greatly. At the injection time of 36.7 min, the crack penetrates the upper and the lower interlayers. With the increasing of the horizontal stress coefficient (from 1.0 to 1.2), the length of the crack extending forward decreases gradually and the propagation direction deflects to the minimum principal stress (σ_3). The fractures only go through the upper interlayer when the horizontal stress coefficient is 1.1 and 1.2 because of the crack deflection. The stress concentration occurs at the boundary between the coal seam and the upper layer. The stress concentration become more significant and the fractures at the boundary are more developed with increasing horizontal stress coefficient.

Figure 6 shows the hydraulic fracture number at different K conditions in heterogeneous coal seam. Known from the figure, the fracture number is five, five and seven when K is 1:1, 1.1:1 and 1.2:1 respectively. The numbers of fractures are the same when K is 1.0 and 1.1, while it gets the most when K is 1.2 because of the stress concentration at the boundary. So the number of secondary fractures can increase greatly in both cases of increasing horizontal stress coefficient and interlayer.

The relation curve between fracturing area and fracturing time is shown in figure 7. From the figure, the fracturing area decreases with increasing K and the fracturing areas are 44.2 m², 30.4 m² and 24.3 m², respectively. The horizontal stress coefficient has great effect on fracturing area. Even if it has the most fracture number when K is 1.2, its fracturing area is the minimum. At the initial stage of hydraulic fracturing, the fracturing area increasing rapidly, and the growth rate reduces gradually. That is because multiple circulation channels block the rapid propagation of hydraulic fracture. We should control the increase of

Table 3. Initial fractured pressures in different K conditions.

K	1.0	1.1	1.2
Initial pressure/MPa	13.6	13.4	13.25

where $K = \sigma_1 / \sigma_3$.

Figure 3. Fracture propagation in heterogeneous coal seam when K is 1.0.

Figure 4. Fracture propagation in heterogeneous coal seam when K is 1.1.

Figure 5. Fracture propagation in heterogeneous coal seam when K is 1.2.

Figure 6. Fracture number under different K conditions in heterogeneous coal seam.

fracture height and width appropriately to improve the fracturing area.

Based on the initiation and propagation model established in section 2, the effect of multiple factors including coal elasticity modulus and fracturing fluid displacement on fracture geometry, are quantitatively studied. The basic parameters of the coal seam are shown in tables 1 and 2, and the horizontal stress coefficient is constant 1.2.

3.1 The effect of coal elasticity modulus on fracture geometry

The other parameters are kept constant to study the effect of coal elasticity modulus on fracture geometry. The input coal elasticity modulus is increasing from 3 GPa to 8 GPa with an increment of 1 GPa.

The coal elasticity modulus has great effect on fracture geometry. Figure 8 shows the relation of fracture length

Figure 7. Fracturing area under different K conditions in heterogeneous coal seam.

Figure 8. Relation of fracture length and maximum crack width with different coal elasticity modulus in heterogeneous coal seam.

and maximum crack width with coal elasticity modulus. The length and the maximum width of the major fracture both decrease linearly with increasing coal elasticity modulus which indicates that the fracture is difficult to extend in high elasticity modulus of coal.

3.2 The effect of fracturing fluid displacement on fracture geometry

In this section, the effect of fracturing fluid displacement on fracture geometry is described. We keep the other parameters constant, the fluid displacement increases from $3 \text{ m}^3/\text{min}$ to $6 \text{ m}^3/\text{min}$ with an increment of $0.5 \text{ m}^3/\text{min}$. Figure 9 shows the relation of length and maximum width of the major fracture with fracturing fluid displacement.

Figure 9. Relationship of fracture length and maximum width with fracturing fluid displacement in heterogeneous coal seam.

The fracture length and the maximum fracture width show completely opposite changed tendencies with the increase of fracturing fluid displacement. The fracture length decreases with increasing fluid displacement and the decreasing rate decreases gradually. It presents a descending trend of exponential function. However, the maximum fracture width increases with increasing fracturing fluid displacement. This is because the larger the fracturing fluid displacement, the greater the tangential flow resistance in the fracture and the more difficult the crack extension.

Figure 10 shows the fracture shape curves. The major fracture becomes short and wide with increasing fracturing fluid displacement while it grows long and narrow with decreasing fracturing fluid displacement.

Figure 10. Fracture shapes under different fracturing fluid displacement conditions in heterogeneous coal seam.

4. Summary and conclusions

- (1) The fracture initiation begins at the perforation interval and the hydraulic fractures distribute symmetrically along the perforation midpoint. The fracture length decreases with the increase of the horizontal stress coefficient and the fracture turns to the minimum principal stress direction. The inhomogeneity of stress is detrimental for the formation of multiple cracks and hydraulic fracturing area decreases with increasing stress heterogeneity.
- (2) Because of the existence of the interlayers, stress concentration occurs at the boundary of reservoir and the upper layer when the hydraulic fracture goes through the interlayers. With the increase of the horizontal stress coefficient, the cracks at the boundary have changed from less developed to more developed.
- (3) The coal elasticity modulus and fracturing fluid displacement play a determinative effect on fracture geometry. The length and the maximum width of the major fracture decrease linearly with increasing coal elasticity modulus. The major fracture becomes short and wide with increasing fracturing fluid displacement while it grows long and narrow with decreasing fracturing fluid displacement.

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Nomenclature

CBM	coalbed methane
u_x	flow rate along x direction
u_z	flow rate along z direction
u	fracturing fluid viscosity
q_x	volume flow rate per unit length along x direction
q	fracturing fluid flow at one side
q_i	fracturing fluid displacement
h_f	maximum fracture height
w	fracture width
w_0	maximum fracture width
L	half-fracture length
P	fracture plane pressure
p_0	initial injection pressure
σ_n	normal closure pressure
σ_{teff}	effective stress of new fracture tip
$\sigma_{H,min}$	minimum horizontal principal stress

$\sigma_{H,max}$	maximum horizontal principal stress
P_{frac}	hydraulic fracturing pressure
σ_t	tensile strength of coal
Δp	pressure drop of the fracturing fluid
θ	included angle between hydraulic fracture and natural fracture

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