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The Research on Dynamic Rules of Crack Extension during Hydraulic Fracturing for Oil Shale In-Situ Exploitation*

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Abstract

It is a tough problem of low permeability for in-situ exploiting oil shale, while improving low permeability by hydraulic fracturing can generate permeable belts, and this is vital importance for oil exploitation. According to the layer property of oil shale, making full use of cohesive element to simulate, it established mathematical models for hydraulic fracturing and its fracturing rules, then conducted 3D numerical simulation. We can get: the shape of fractures is oval, and fractures extend along different directions are different, due to anisotropic property of oil shale and geostatic stress influenced, shown as from fig.9 to fig.10; the leak-off flow rate of fracturing fluid rises, reduces, and tends to a fixed value shown in fig.11; fracture opening is dependant on the volume and injection velocity of fluid injection and the rules of damage evolution and fracturing opening refer to fig.5, fig.6 and fig.13.

Keywords:oil shale；hydraulic fracture；crack extension；leak-off

1. Introduction

Oil shale is a kind of sedimentary rock with high-ash and tightly layered which can generate shale oil after chemical carbonization[1、2]. So far, it is predicted that the oil shale which is more than 14000 million tons can be used for industrial production in China. Moreover, the amount of oil shale has ascertained equals to the total reserves of natural oil in China.

By far, the main exploitation technique for oil shale is ground carbonization all over the world [3-5]. However, this has polluted the environment seriously. Accordingly, the countries which are rich in oil

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shale and other energy corporations begin to put a new premium on distilling oil shale in-situ directly. For examples, Royal Shell Corporation in Dutch is developing the way that electrical heating the oil shale[6、7、8]. In 2004, professor Yangsheng Zhao in Taiyuan University of Technology came up with a new solution named fracturing to group of wells by injecting superheated steam into in-situ oil shale to make it thermal decomposition which can generate oil and gas carried by steam in to the ground [9]. The key to this technique is to generate permeable belts for oil and gas by hydraulic fracturing among group of wells. Eventually, specialists and scholars around the world have carried out research in theories and numerical simulations about hydraulic fracturing [10-11], while most numerical simulations concentrates
on the size of crack apart from dynamic parameter in the process of dynamic extension such as scope, path, direction and so on. According to the property of oil shale, making use
of cohesive element to simulate hydraulic fracturing to generate permeable belts, this is vital importance for oil exploration. Due to the property of oil shale, using cohesive element to simulate, it establishes mathematical models for hydraulic fracturing and its fracturing rules. On the condition that injecting high pressure fracturing fluid into pre-crack in oil shale, it conducts the numerical simulation. We can get the rules of stress distribution and pore pressure of oil shale including crack dynamic extension rules, fracturing fluid filtrating loss rules and how the amounts of fracturing fluid injected affects crack extension in the progress of hydraulic fracturing. In the end, the research will offer a theoretical basis and guidance to actual project.

2. Establishing mathematical models for hydraulic fracturing

The mathematical models for hydraulic fracturing contain the equilibrium equations of deformation field, geometric equation, seepage field equations and fracturing rules for the interface of oil shale layer.

(1) The equilibrium equations

Ignoring inertia force, momentum conservation equation can be simplified as static equilibrium equations:

$$\partial \sigma_{ij} / \partial x_j + F_i = 0 \tag{1}$$

Where F_i is the component of body force .

(2) Geometric equation

$$d\varepsilon_{ij} = (\partial du_i / \partial x_j + \partial du_j / \partial x_i)/2 \tag{2}$$

Where u_i is the component of displacement.

(3) Drucker-Prager criterion

$$F = \alpha I_1 + \sqrt{J_2} = k \tag{3}$$

Where I_1 and J_2 indicate the first invariant of stress tensor and the second invariant deviatoric tensor of stress, respectively; α and k are constants which are the function of angle of internal friction φ and cohesion c .

(4) Seepage field equations

$$\begin{aligned}&\phi \cdot (\partial \rho_l / \partial t) + \rho_l [\partial \varepsilon_V / \partial t + ((1-\phi)/\rho_s) \cdot (\partial \rho_s / \partial t)] \\ &\quad = -\nabla : [-K(\phi) \cdot K_{rl} I (\nabla p - \rho_l g \nabla z)]\end{aligned} \tag{4}$$

Where ϕ is void ratio of oil shale; ρ_s and ρ_l indicate the density of framework and liquid, respectively; $K(\phi)$ is the coefficient permeability which is a function of void ratio;

K_{rl} is relative permeability which is a function of saturation

(5) Fracturing rules for interface of oil shale layer

Making use of cohesive element to simulate layered interface of oil shale and its relationship between stress and strain, we can get:

$$t = \begin{bmatrix} t_n \\ t_s \\ t_t \end{bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix} \begin{bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{bmatrix} = K\varepsilon \quad (5)$$

Where the nominal traction stress vector, t, consists of three components: t_n, t_s and t_t, which represent the normal and the two shear tractions, respectively. The corresponding separations are denoted by δ_n, δ_s, and δ_t. Denoting by T_0 the original thickness of the cohesive element, the nominal strain can be defined as

$$\varepsilon_n = \delta_n / T_0, \quad \varepsilon_s = \delta_s / T_0, \quad \varepsilon_t = \delta_t / T_0 \quad (6)$$

Damage is assumed to initiate when a quadratic interaction function involving the nominal stress ratios (defined in the expression below) equals one. This criterion can be represented as

$$\left(t_n / t_n^0\right)^2 + \left(t_s / t_s^0\right)^2 + \left(t_t / t_t^0\right)^2 = 1 \quad (7)$$

The damage evolution law describes the rate at which the material stiffness is degraded once the corresponding initiation
criterion is reached.

For linear softening, use an evolution of the damage variable D, that reduces to

$$E = (1 - D)E_0 \quad (8)$$

$$D = \delta_m^f \left(\delta_m^{\max} - \delta_m^0\right) / \left(\delta_m^{\max}\left(\delta_m^f - \delta_m^0\right)\right) \quad (9)$$

Where $\delta_m^f = 2G^c / T_{elf}^o$ with T_{elf}^0 as the effective traction

at damage initiation, $\delta_{\mathrm{m}}^{\max}$ refers to the maximum value of the effective displacement attained during the loading history.

3. Numerical simulation

3.1. Calculation condition

3.1.1. Geometric model

Due to symmetry properties, it simulates one-quarter of the model, as shown in figure 1. In the drawing, there are three colors stand for top plate, oil shale and bottom plate, respectively. In the mean time, the size of the model is 200m×200m×40m, and the thickness of oil shale reservoir is 10m.

3.1.2. Rock mechanics parameters

The basic mechanics parameters of model can be seen in table 1, table2, figure 3 and figure 4 respectively.

3.1.3. Boundary conditions and loads

The two symmetry planes are endowed with symmetrical displacement and impermeable boundary conditions whose normal directions are the crack length and width propagation direction respectively. Apply gravity pressure to top surface and fixed displacement and pore pressure boundary conditions. Set nodes of pre-crack a certain flow velocity.

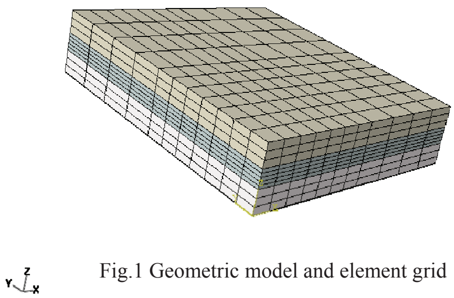

Fig.1 Geometric model and element grid

Table 1 Basic mechanics parameters of oil shale

Title	ρ/(kg/m³)	E/kpa	υ	ϕ /(°)	σ/(kpa·s⁻¹)	φ /(°)
Top plate	2500	4.137×10^6	0.15	28	1.0	28
Oil shale	2500	1.2×10^7	0.22	36	0.95	36
Bottom plate	2500	6.25×10^6	0.19	30	1.0	30

Table 2 Basic mechanics parameters of layered interface

Title	*E/kpa*	t_n^0 /kpa	t_s^0 /kpa	t_t^0 /kpa	G_n^c /(N·mm)	G_s^c /(N·mm)	G_t^c /(N·mm)
Oil shale	8.5×10^7	0.32	0.32	0.32	28	28	28

3.2. The calculation and analysis

3.2.1. Stress and damage analysis

The internal stress of oil shale increases gradually coupled with injected fracturing fluid and crack tip appears stress concentration. When stress of crack tip comes up to the threshold value, crack will be further expanded. Figure 4 shows the first principle stress of oil shale when injection period is 300 seconds. (Deformation has been magnified six hundred times)

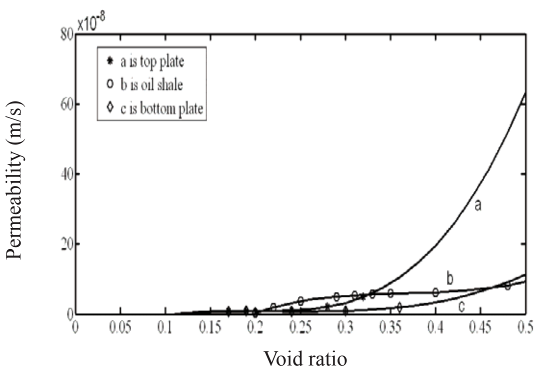

Fig.2 Coefficient curves of permeability and void ratio

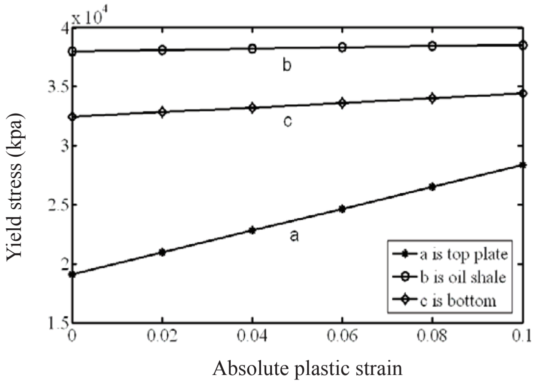

Fig.3 Curves of plastic harden

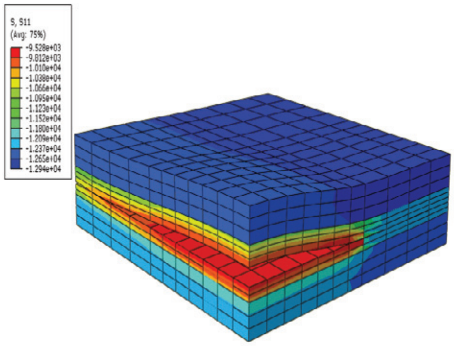

Fig.4 The first principle stress

The curves shown in figure 5 respectively shows damage evolution laws of cohesive elements at different distance from wellbore when fracturing fluid is injected at different times.As a whole, crack extends constantly along the direction apart from wellbore.

3.2.2. Analysis crack dynamic extension rules

The shape of fractures is oval as Fig 6 shows. In this image, red zone represents the region affected by crack and other colors stand for cohesive elements which can not be influenced by crack at all. In other words, cohesive elements in these regions will not begin to damage. (In fig6 deformation has been magnified six hundred times)

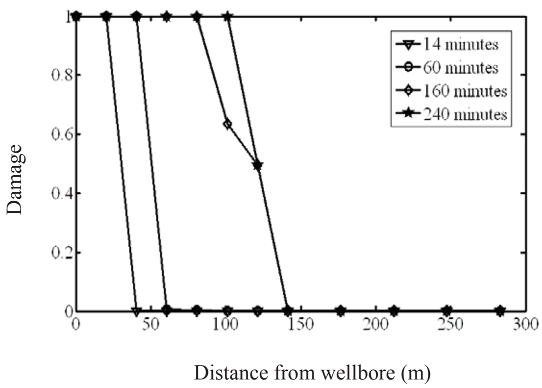

Fig.5 Damage evolution rules of cohesive elements

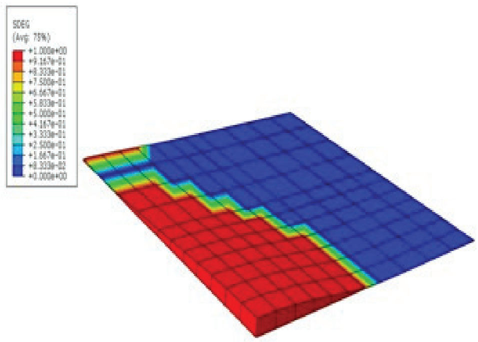

Fig.6 Destructive processing of cohesive elements and crack shape

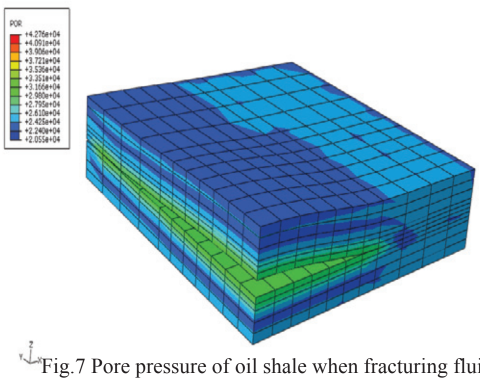

Fig.7 Pore pressure of oil shale when fracturing fluid injected on 300 seconds

With time accumulated, there is more and more fracturing fluid injected into oil shale and pressure in oil shale increases. As a result, crack extends along X-direction and Y-direction respectively while the velocity of fracturing for Y-direction is larger than that of X-direction, due to anisotropic property of oil shale and geostatic stress. As the following figures show:

From figure 10, crack has extended at a distance 60m from wellbore when fracturing fluid is injected on 140 seconds. After that, crack extending along Y-direction becomes easier than before, because fracturing fluid flow rate speeds up coupled with cohesive elements of layer interface damaging initiation and evolution till to fail completely and release the energy.

3.2.3. Analysis leak-off for fracturing fluid

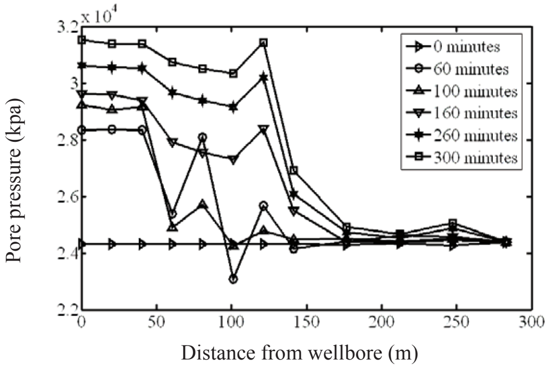

Fig.8 Curves of the pore pressure in interface of oil shale layer when fracturing fluid injected at different time

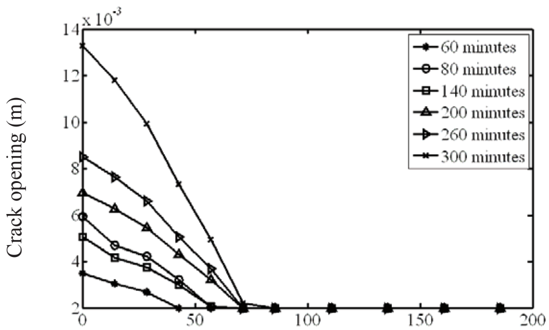

Fig.9 Curves of fracture extend along X-direction when fracturing fluid injected at different time

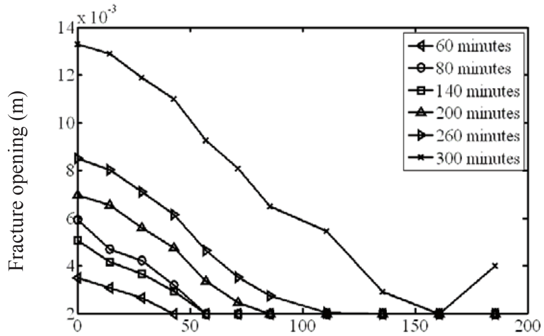

Fig.10 Curves of fracture extend along Y-direction when fracturing fluid injected at different time

As fracturing fluid injected into oil shale, leak-off flow rate begins to rise at the peak point and then descends to a stable value. This is because an initial injection for fracturing fluid, the crack has not been formed, fracturing liquid from cracking layer to the top plate and bottom plate. However, with fracturing fluid accumulated more and more in the layer interface, the cohesive elements began to damage and evolute till total failure. As a result, this leads to leak-off flow rate decline. On the whole, accumulated leak-off flow goes to rise all the time, the following figures shows.

3.2.4. The rules of the amount of fracturing fluid injected impacting on fracture opening

For the simulation, the injection speed of fracturing fluid ranges from $0.1m^3/s$ to $0.4m^3/s$. As is known to all, fracture opening will become larger and larger with fracturing fluid accumulated in oil shale. Meanwhile, on the case of a certain volume of fracturing fluid injected, fracture opening increases.

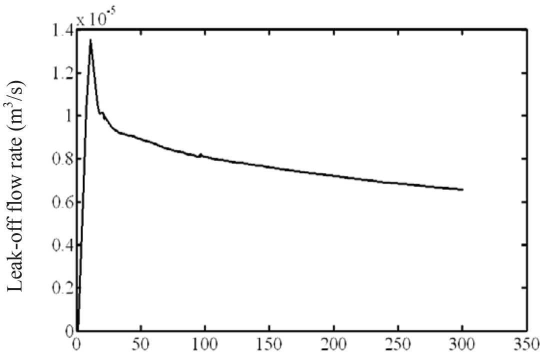

Fig.11 Curve of leak-off flow rate

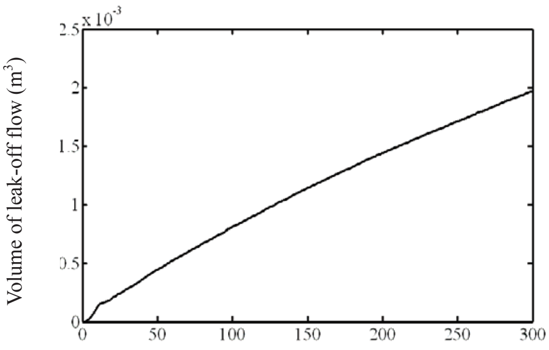

Fig.12 Curve of accumulated leak-off flow

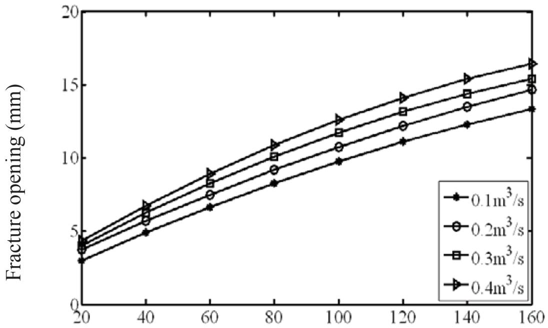

Fig.13 Curves of fracture opening and the volume of fracturing fluid injected

4. Conclusion

With regard to underground heating to exploite in-situ oil shale, hydraulic fracturing is an effective measure to improve permeability. According to the property of oil shale, picking up the cohesive element to simulate, we can get:

(1) Cohesive elements can reflect truly the layer property of oil shale. The internal stress of oil shale increases gradually coupled with fracturing fluid which is injected into the pre-crack constantly, and crack tip will appear stress concentration. When stress of crack tip comes up to the threshold value, crack will be further expanded. Meanwhile, the shape of fractures is oval.

(2) Due to anisotropic property of oil shale and geostatic stress influenced, crack extends along X-direction and Y-direction respectively, while the velocity of fracturing for Y-direction is larger than that of X-direction. Because fracturing fluid flow rate speeds up along cohesive elements of
oil shale layer interface and evolute till to fail completely and release the energy, crack extending along Y-direction becomes easier than before.

(3) As fracturing fluid injected into oil shale, leak-off flow rate begins to rise at the peak point and then descends to a stable value. On the whole, accumulated leak-off flow goes to increase all the time.

(4) Fracture opening will become larger and larger with fracturing fluid accumulated in oil shale. Meanwhile, in the case of a certain volume of fracturing fluid injected, fracture opening increases.

As a result, it is a key to choose reasonable velocity and volume of fracturing fluid injected to improve permeability of oil shale based on practical engineering requirement.

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