



A simulation method based on energy criterion for network fracturing in shale gas reservoirs

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ABSTRACT

The fracture network in shale gas reservoirs has a plurality of extending frontiers and the propagation paths of fractures are difficult to predict in advance. When the network fracturing is simulated by the extended finite element method (XFEM) based on stress intensity factors, the computation is arduous and time-consuming, which limits the application of XFEM in field fracturing design. Therefore, a simulating method of crack propagation based on energy criterion is proposed. Based on the principle of energy balance, the energy criterion for controlling crack frontiers extending is established by the fluid injection energy, the rock strain energy, the surface energy, the seismic energy and the friction loss energy. The criterion only needs to calculate the energy distribution in the crack frontiers to judge whether the fracture could expand, avoiding the fussy calculation of the stress intensity factor. Based on the proposed energy criterion, the fluid solid coupling effect and the fractures interaction, an energy method is established for network fracturing simulation in shale gas horizontal well. The results show that the fracture network morphology obtained by simulation is basically consistent with micro-seismic monitoring result, and the computational efficiency of this simulation method is 10000 times higher than that of XFEM. The energy method provides an idea and basis for the simulation and design of shale reservoir fracturing.

1. Introduction

The horizontal well with segmented volume fracturing is the main technology to exploit the shale gas effectively. The complex network is formed during the hydraulic fracturing process for shale reservoirs via the micro-seismic monitoring. Thus, the investigation of the formation mechanism and simulation of fracture network is essential (Wu et al., 2012; Zou et al., 2015; Fisher et al., 2004, 2005) and the criterion of rock failure and fracture extension is the key step. The calculation complexity and time consumption of the fracture network models are significantly different when different criterions of fracture propagation are used in numerical simulations. Therefore, the criterion study of rock failure and fracture propagation for shale reservoir fracturing plays a vital role in characterizing the formation of the fracture network.

Most of the current fracture propagation models are on the basis of stress intensity factor (SIF) (Irwin, 1957). Some complex fracture network models such as the wire-mesh model (Xu et al., 2009), the unconventional fracture model (Weng et al., 2011) and the discrete network model (Meyer, 1989; Meyer and Bazan, 2011) are established. These models are solved by different numerical algorithms, such as

boundary element (Olson and Taleghani, 2009; Hou et al., 2015), extended finite element (Taleghani, 2010; Zeng et al., 2015) and discrete element (Meyer, 1989; Meyer and Bazan, 2011; Wang et al., 2015). The fracture criterions used in the mentioned models include the maximum energy release rate criterion, the minimum strain energy density criterion and the maximum tensile stress criterion (Zhao, 2004), and the theoretical foundation of these criterions is the SIF calculation based on the fracture toughness criterion. However, the fracture network has many propagation frontiers and the fracture geometry is very complex, making it difficult to calculate the stress distribution accurately. And the establishment of the integral path to calculate SIF is sometimes impossible (Martin, 2000). In addition, the calculation of network simulation is very time-wasting based on the fracture toughness criterion, which deviates from the engineering demand.

Therefore, we attempt to study hydraulic crack propagation from the viewpoint of energy balance. Salamon (1984) established the energy balance law for rock failure processes during the mining course and developed methodologies for calculating energy terms in rock mechanics. Yao et al. (2018) assumed that the fractures extend forward when hydraulic energy is greater than the sum of strain energy and

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surface energy, but the friction dissipation energy was not taken into account when using the Griffith stability criterion. Khademian (2016); Khademian et al. (2017) focused on the radiated seismic energy during fracturing. They calculated strain energy, friction work, dissipative plastic work, and radiated seismic energy for analyzing rock failures in compression or shear. Forasmuch as, the energy criterion controlling the extension of fracture frontiers is established by balancing hydraulic fracturing injection energy, strain energy, surface energy, seismic energy and friction loss energy based on the above theories. Then an energy method for fracturing simulation of shale gas horizontal well is proposed combined with the energy criterion and the fluid-solid coupling method used to calculate fracturing fluid flow rate and pressure distribution in the fracture network. The energy method avoids the complex calculation of SIF in the crack frontiers of fracture network and provides an idea and basis for the fracturing simulation and design in shale reservoirs.

2. The energy mechanism and propagation criterion of fracture network formation

2.1. Energy mechanism of fracture network formation

The hydraulic fracturing is a dynamic coupling process of rock deformation and fracturing fluid flow. On one hand, the micro-cracks occur inside the rock under the pressure of the fracturing fluid, and gradually propagate through the rock. Ultimately, the macro-cracks are formed. On the other hand, the fracturing fluid flows in the cracks and supports a certain width of cracks. With the high displacement injection of the fracturing fluid, the fluid pressure increases instantaneously, forcing the cracks to expand continuously.

The hydraulic fracture would encounter natural fractures during the expansion process of fracture. When the hydraulic energy supplied by the fracturing fluid is greater than the energy required by natural crack propagation at both crack tips, the crack branches would be formed. Then the branch cracks continue to propagate. The branch cracks will form branches once again if the fractures run into the other natural fracture. In this way, the fracture network consisting of hydraulic cracks and natural fractures is eventually formed. Hydraulic fractures not only form branches with natural fractures, but also produce bifurcation, which finally produces the crack system like a root. In the shale reservoir, the complex fracture network shown in Fig. 1 is composed of natural fractures, hydraulic fractures and induced joints.

2.2. Energy criterion for crack propagation

During the hydraulic fracturing process, the energy in the cracks mainly contains the following parts (Fig. 2): the hydraulic energy of fracturing fluid (E_k); surface energy (U) to form new cracks; the rock strain energy (E_s) which is equivalent to the work done by the fluid pressure; hydraulic friction loss energy (E_f) including the internal friction loss of fracturing fluid and friction loss between fracturing fluid and cracks wall; seismic energy (E_w) that monitored by micro-seismic during the fracturing process. Since micro-seismic energy is very small compared to the total hydraulic energy, it is ignored in our study.

On the basis of the formation of the complex fracture network after fracturing in shale reservoir, without considering the bifurcation of the fracture itself, an energy criterion for the expansion of the whole fracture network under the condition of fracture classification is given.

When $\sum E_k > \sum (U + E_s + E_f)$, the hydraulic fractures begin to propagate; when $\sum E_k < \sum (U + E_s + E_f)$, the hydraulic fractures cease to expand.

The physical quantities in the energy criterion are calculated by Eqs. (1)–(4).

Total injected hydraulic energy is

$$\sum E_k = (q - q_i^i) \left(\sigma_{\min} + S_t + \sum_{i=1}^n \sum_{j=0}^N \Delta p_{ij} \right) \sum_{i=1}^n t_i \quad (1)$$

The whole surface energy of fracture network is

$$U = \sum_{i=1}^n \sum_{j=0}^N \gamma_s h_{ij} l_{ij} \quad (2)$$

The strain energy of rock is

$$\sum E_s = \sum_{i=1}^n \sum_{j=0}^N \sigma_{\min} h_{ij} l_{ij} \bar{w}_{ij} \quad (3)$$

The frictional loss energy is

$$\sum E_f = (q - q_i^i) \sum_{i=1}^n t_i \sum_{j=0}^N \Delta p_{ij} \quad (4)$$

where i represents the i -th time step in the iterative calculation; j represents the j -th level fracture; q is the pump rate, m^3/s ; $T = \sum_{i=1}^n t_i$ is the injection time of fracturing fluid, s ; σ_{\min} is the minimum principal stress, MPa ; S_t is the tensile strength, MPa ; Δp_{ij} is the pressure drop in the fracture, MPa ; γ_s is the rock surface energy density, J/m^2 ; h_{ij} is the fracture height, m ; l_{ij} is the fracture length, m ; \bar{w}_{ij} is the average fracture width, $\bar{w}_{ij} = (w_{i-1,j} + w_{i,j})/2$, m .

According to previous studies, the reservoir rock is in the state of drastic change of local ground stress field. The I-II mixed fracture usually occurs during the process of hydraulic fracturing. For the two-dimensional plane, the rock surface energy density (Nuismer, 1974; Aimene and Nairn, 2014) of the I-II type mixed fractures can be expressed as Eq. (5).

$$\gamma_s = \frac{(K_{IC}^2 + K_{IIC}^2)}{2E'} \quad (5)$$

In the case of plane stress: $E' = E$; plane strain: $E' = E/(1 - \nu^2)$; K_{IC} and K_{IIC} are I and II rock fracture toughness respectively, which could be measured by laboratory experiments.

3. Dynamic mechanism and numerical solution of fracture network propagation

3.1. Dynamic mechanism of fracture network propagation

Dynamic mechanism of fracture network expansion was studied from the perspective of fracture dynamic mechanics (Zhao et al., 2012). When hydraulic fracture encounters the natural fractures, it is considered that the formation of complex fracture network needs to simultaneously meet the extending conditions at both ends of the natural fractures. The pressure required for the simultaneous propagation of both ends of the natural fracture is higher than the pressure required by the quasi-static expansion of the previous fracture. The fracture dynamics is used to determine the critical pump rate which could achieve the simultaneous expansion of branch cracks.

The mechanism of the network expansion is studied from the perspective of energy in this paper. When hydraulic fracturing is carried out with large and variable pump rate, there is obvious dynamic shock wave in the stratum. A large number of micro seismic events is captured by the micro seismic monitoring technology. In the meantime, the stress state of rock and the tip position of crack vary with time rapidly. The inertial terms of the system balance equation can't be neglected when the fluid and rock are taken as a whole. Therefore, the crack propagation should be treated as a dynamical problem in this case.

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