Numerical Simulation of Fracture Sequence on Multiple Hydraulic Fracture Propagation in Tight Gas Reservoir

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Abstract. Hydraulic fracturing with horizontal well is an effective technology for the unconventional resources development, especially for the shale gas, tight gas and oil. Simultaneous fracturing, sequential fracturing and alternating fracturing were the main technologies applied in the horizontal well stimulations. Based on the extended finite element method, the 2D seepage-stress-damage models for simulating fracture propagation of simultaneous fracturing, sequential fracturing and alternating fracturing were proposed to investigate the influence of fracture sequence on fracture propagation and fracture aperture. From the simulations, the sequential fracturing and alternating fracturing can dramatically decrease the limitation on fracture propagation caused by “stress shadow”, the total fracture length increased by 20.6% and 26.1% compared with simultaneous fracturing. The fracture aperture also affected by the fracture sequence. The simulation results demonstrates that the alternating fracturing is an effective method to prevent the fracture width reduction caused by squeezing effect, which can effectively improve the well productivity. These simulations are useful for horizontal wellbore stimulation design to acquire the desired fracture lengths, fracture conductivity and production rates.

Keywords: Hydraulic fracture; XFEM; fracture sequence; numerical simulation.

1. Introduction

Due to the low porosity and permeability of the unconventional formation, hydraulic fracturing of horizontal well hydraulic fracturing technology is the key technology for the development of unconventional resources[1, 2]. In order to achieve a desired stimulated rock volumes and fracture networks, it is necessary to understand the effect of various rock and fluid properties on stimulation to minimize the risk of unwanted fracture geometries[3-5]. In this paper, the influence of simultaneous fracturing, sequential fracturing and alternating fracturing on fracture propagation and stress field changing were analyzed. In addition, the fracture conductivity was the main parameter to improve the well production. In order to investigate the effect of fracturing sequence on fracture aperture, the propped and unpropped fractures were compared to evaluate the reduction of fracture width caused by fracturing sequence.

2. Methodology

2.1. Constitutive Equation

The fracture propagation criterion based on linear elastic fracture mechanics (LEFM) assumes that there is a fracture process zone near the fracture tip. Compared with the fracture size, the material shows very
little inelastic behavior. Fracture propagation occurs when the stress intensity factor exceeds the material strength. Nevertheless, the adequacy of this assumption is questionable because fracture propagation in quasi-brittle and ductile materials leads to significant plastic deformation around the fracture tip because of a shared failure. In addition, even for fragile materials, the fracture course area can become concentrated at a single point, and initial cracks need to exist for LEFM to apply. The bond zone model is a simple model that is suitable for processing zones and materials that fail as a result of crack propagation and coalescence[6].

The constitutive behavior of the viscous region is defined by the traction–separation relationship. The elastic behavior is represented by an elastic constitutive matrix, which links the normal stress and shear stress with the normal and shear separation of crack elements.

\[
\begin{align*}
\mathbf{t} &= \left\{ \begin{array}{c}
t_n \\ t_s \\ t_t
\end{array} \right\} = \left[ \begin{array}{cc}
K_{nn} & 0 \\
0 & K_{ss} \\
0 & 0 
\end{array} \right] \left\{ \begin{array}{c}
\delta_n \\ \delta_s \\ \delta_t
\end{array} \right\} = K \delta
\end{align*}
\]

The nominal traction stress vector \( \mathbf{t} \) consists of the components \( t_n, t_s, \) and \( t_t \), which represent the normal and the two shear tractions, respectively. The corresponding separations are denoted by \( \delta_n, \delta_s, \) and \( \delta_t \).

2.2. Fracture Propagation Criterion

In this research, the material stiffness degradation is introduced to describe the damage evolution law once the corresponding initiation criterion is reached. In this model, the damage law is described as follows[7].

\[
\begin{align*}
t_n &= \begin{cases}
(1-D)t_n, & t_n > 0 \\
t_n, & t_n \leq 0 
\end{cases}
\end{align*}
\]

\[
t_s = (1-D)t_s
\]

\[
t_t = (1-D)t_t
\]

where \( D \) is the overall damage degree, which changes from 0 to 1. When it is 0, it means that the material is not been damaged; when it is 1, it means that the material is damaged completed. The \( t_n, t_s, \) and \( t_t \) are the stress components determined by the traction-separation criterion.

\[
D = \frac{\delta^f (\delta_{\text{max}}^f - \delta^0)}{\delta_{\text{max}}^f (\delta^f - \delta^0)}
\]

Where \( \delta_n = \sqrt{(\delta_n)^2 + (\delta_s)^2 + (\delta_t)^2} \).

3. Simulation and Results

A multistage fracture propagation model based on the finite element method was established. The model was 180 m in the X direction (along the wellbore and parallel to the minimum horizontal principal stress), 180 m in the Y direction (perpendicular to the minimum horizontal principal stress). The target formation is a sand-rich formation, so the model was treated as pure sand, and no interlayer was built in the model. The fracture space was 30 m. To study the fracture propagation simultaneously, a model with three fracture planes was built. The injection points in this model represented the perforating holes. The input parameters in the model are listed in Table. 1.
Table 1. Input parameters for the fracture propagation model

| Parameter                        | Unit            | Value  |
|----------------------------------|-----------------|--------|
| Young’s modulus                  | $\times 10^3$ MPa | 28.6   |
| Poisson’s ratio                  | Dimensionless   | 0.215  |
| Porosity                         | %               | 2.7    |
| Permeability                      | $10^{-3} \mu m^2$ | 0.014  |
| Initial pore pressure            | MPa             | 38.41  |
| Vertical stress                  | MPa             | 74.42  |
| Minimum Horizontal Principle stress | MPa             | 57.43  |
| Maximum Horizontal Principle stress | MPa             | 66.53  |

Fig. 1 was the fracture geometry of simultaneous fracturing. In this case, no proppant was pumped in the simulation. The fractures from right to left were Fracture a, Fracture b, Fracture c and Fracture d. From the simulation, when the time was 100 s, the middle fractures (Fracture b and Fracture c) were a little shorter than our fractures (Fracture a and Fracture d), and the four fractures propagated along the straight line. When the time was 200 s, the outer fractures deviated from the initial minimum principal stress direction during the propagation process. When the time was 300 s, there was an obvious “enwrapped” phenomenon because of the outer fractures were longer than the inner fractures, and the deviation angles of outer fractures between the adjacent fracture and the initial maximum principal stress were 18°. The length of the four fractures were 53m, 38m, 39m and 54m.

Figure 1. Fracture geometry of simultaneous fracturing.

The sequential fracturing geometry is shown in Fig. 2. After injection of 300 s, it is vividly depicted that the Fracture a propagates along the straight line. However, with the passage of time (after 200 s), the Fracture b curve away from the first fracture, the deflection angle of the Fracture b was 11°. Moreover, the width of Fracture a experienced an obvious reduction. After 1300 s time period of fracturing fluid injection, the length of Fracture c was less than the former two fractures, and the deflection angle of the third fracture was less than that of Fracture b. What’s more, the initiation and propagation also caused the fracture width reduction of Fracture b. When the last schedule was carried out (after 1800 s injection), the Fracture d was longer than the Fracture b and c, but less than the Fracture a. In addition, the fracture aperture of Fracture d was greater than the former three fractures. After 1800 s injection, The length of four fractures were Fracture a (64 m), Fracture b (52 m), Fracture c (48 m), and Fracture d (58 m).

The alternating fracturing geometry is shown in Fig. 3. After injection of 300 s and 800 s, the Fracture a and Fracture b can propagate along the straight line, but length of the Fracture b was shorter than that of Fracture a. However, with the passage of time (after 1300 s), the Fracture c initiated and propagated in the middle of Fracture a and Fracture b, but the extension length was shorter than Fracture b. The fracture width of Fracture a and Fracture b experienced an obvious reduction due to the propagation of Fracture c. After 1800 s time period of fracturing fluid injection, the Fracture d propagated next to Fracture c. The length of Fracture d was slightly shorter than Fracture b, but longer than Fracture c. In addition, the propagation of Fracture d also caused the fracture width reduction of Fracture c. After
injection, the length of four fractures were Fracture a (64 m), Fracture b (60 m), Fracture c (51 m), and Fracture d (57 m).

![Figure 2](image1.png)  ![Figure 3](image2.png)

**Figure 2.** Fracture geometry of sequential fracturing.  
**Figure 3.** Fracture geometry of alternating fracturing.

4. Conclusion

The minimum principle stress deflection could dramatically increase the fracture propagation pressure, which was the main reason account for non-uniform of fracture length. From the simulations, the fracture propagation under simultaneous fracturing showed obviously non-uniform, an obvious “enwrapped” phenomenon appeared in the simulation. While the alternating fracturing could dramatically decrease the non-uniform of fracture extension. In addition, the total length of four fractures under sequential fracturing and alternating fracturing were longer than that under simultaneous fracturing, which demonstrated that the sequential fracturing and alternating fracturing could achieve a larger stimulated volume under the same reservoir condition and pumping parameters. Affected by the minimum principle stress deflection, the fracture would deflect during the propagation under the simultaneous fracturing and sequential fracturing, while the fractures would propagate along the straight line under the alternating fracturing, which could effectively enlarge the stimulated volume.

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