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RESEARCH PAPER

Numerical simulation of multi-stage fracturing and optimization of perforation in a horizontal well

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Abstract: Aiming at analyzing the issues of non-uniform growths of multiple hydraulic fractures caused by stress shadowing, a numerical model considering elasto-hydrodynamic, stress interference and flow distribution into different fractures was presented. Based on the model, the effects of perforation friction, perforation cluster spacing, Young modulus of rock and fracturing fluid viscosity on the growth of multiple fractures were investigated. The simulation results show that the growths of hydraulic fractures are relatively uniform with adequate perforation friction; the reduction of perforation cluster spacing, increase of Young modulus or fluid viscosity will cause the reduction of some fracture width and uneven flow distribution into these fractures, thus aggravating non-uniform growth of multiple fractures. Since appropriate perforation friction is conducive to the uniform growth of fractures, a convenient quantitative optimization method to calculate the needed perforation friction for uniform growth was proposed. By estimating inter-fracture induced stress during fracturing, the perforation friction coefficient needed to maintain uniform growth of fractures inside a stage is calculated, and reasonable engineering parameters of perforation can be selected based on this. The perforation parameters of a horizontal well were calculated with the proposed method, the simulation results and actual fracturing performance show that the optimized perforation parameters can effectively keep uniform growth of fractures.

Key words: horizontal well; multi-stage fracturing; fracture growth; perforation friction; perforation optimization; numerical simulation

Introduction

In recent years, development of unconventional hydrocarbon resources has become a hotspot in China[1]. For unconventional reservoirs, multi-stage hydraulic fracturing is a key technical to create highly permeable fractures in rock to increase production[2]. By perforating several clusters of perforations in a stage, multiple hydraulic fractures can be formed concurrently in one injection procedure, lowering fracturing costs significantly. However, a lot of production log data show that some perforation clusters fail to form effective fractures and make any contribution to production[3]. Many related researches indicate that, besides the heterogeneous in-situ stress in reservoirs, stress interference is another important factor causing stunted hydraulic fractures[4–7]. Thus, it is worth to find out how to reduce the negative effect of stress interference, and promote the uniform growth of fractures.

For the past few years, many researchers have studied on the promotion of uniform growth of multiple fractures. Bunger and Peirce[8–9] presented that perforation clusters in specific distribution can reduce the negative effect of stress interference and promote the uniform growth of multiple fractures. However, limited by engineering technology and reservoir condition, placing perforation clusters in specific distribution has its difficulty in practice. Kan Wu and Lecampion[10–11] indicated through numerical simulation that appropriate increase of perforation friction by adjusting the perforation parameters is beneficial to the uniform growth of fractures. Adjusting perforation parameters is an effective way to make multiple fractures grow uniformly and easy to use in engineering practice, but so far there lack applicable optimization methods to quantify these parameters. In this study, a multi-stage fracturing numerical model capturing stress interference and fluid-solid coupling has been presented to analysis factors affecting the non-uniform growth of multiple hydraulic fractures. Also, a convenient method is presented to optimize perforation parameters quantitatively to keep uniform growth.

1. Multi-stage fracturing numerical model

In multi-stage fracturing, the bridge plug is set firstly and two to five perforation clusters are implemented. These perforation clusters are spaced 10–30 m and each cluster typi-

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cally has 6-32 perforations. Then, fracturing fluid is injected, causing several hydraulic fractures to initiate simultaneously from these perforations.

Because the propagation of multiple fractures is a sophisticated process, some assumptions are needed to increase the calculation efficiency of numerical model: (1) the reservoir rock is an isotropic homogeneous elastic body and the fracture growth follows linear elastic fracture mechanics; (2) the fracturing fluid is incompressible Newtonian fluid and the fluid flow in fracture is the Poiseuille flow. In addition, the fracturing fluid leak-off is neglected as most unconventional reservoirs are very low in permeability[12], if needed, the Carter leak-off equation can be introduced in the fracturing model; (3) as only 2–3 MPa horizontal differential in situ stress is effective to suppress the curving of fracture[13], and in most Chinese unconventional reservoirs the horizontal differential stress is much more than 3 MPa, the slight curving of fracture footprints is neglected for simplification.

1.1. Elasticity equations

The x-axis is defined along the direction of the maximum horizontal in situ stress. The multiple fracture footprints are discretized to many element grids with fixed length d_1 (Fig. 1). The relationship between displacements and stresses can be written as equations with displacement discontinuities[14]:

$$\begin{cases} \sigma_{xx} = \dfrac{E}{1+\upsilon}\left[\left(2f_{xy} + yf_{xxy}\right)u_{\mathrm{s}} + \left(f_{yy} + yf_{yyy}\right)u_{\mathrm{n}}\right] \\ \sigma_{yy} = \dfrac{E}{1+\upsilon}\left[\left(-yf_{xyy}\right)u_{\mathrm{s}} + \left(f_{yy} - yf_{yyy}\right)u_{\mathrm{n}}\right] \\ \sigma_{xy} = \dfrac{E}{1+\upsilon}\left[\left(f_{yy} + yf_{yyy}\right)u_{\mathrm{s}} + \left(-yf_{xyy}\right)u_{\mathrm{n}}\right] \end{cases} \tag{1}$$

where the function f is expressed as:

$$f(x,y) = \frac{f_1\left(x+\dfrac{d_1}{2}, y\right) - f_1\left(x-\dfrac{d_1}{2}, y\right) + f_2\left(x+\dfrac{d_1}{2}, y\right) - f_2\left(x-\dfrac{d_1}{2}, y\right)}{4\pi(1-\upsilon)} \tag{2}$$

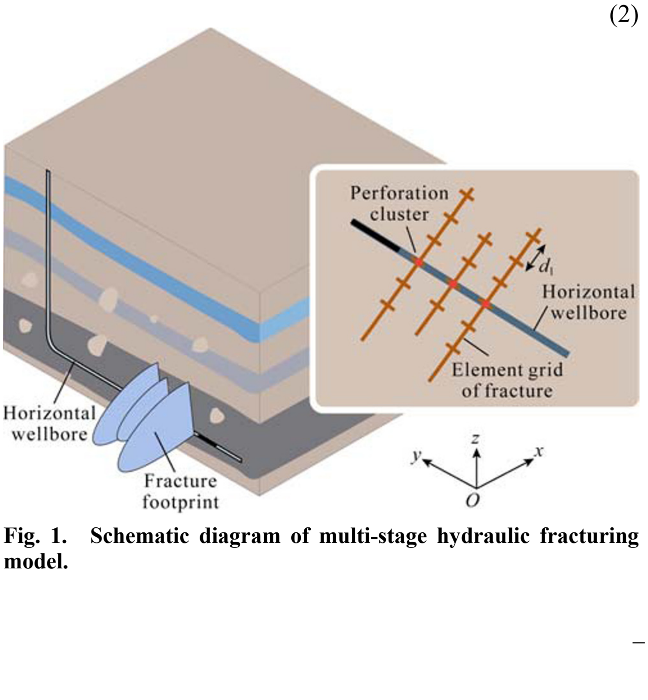

Fig. 1. Schematic diagram of multi-stage hydraulic fracturing model.

$$f_1(x,y) = y\arctan\frac{x}{y} \tag{3}$$

$$f_2(x,y) = x\ln(x^2+y^2)^{0.5} \tag{4}$$

The elasticity equations based on the plane strain assumptions, are suitable for the cases in which fracture height is much larger than fracture length. Thus, in this study these equations are corrected by dimensionless coefficient proposed by Olson[15]:

$$G = 1 - \frac{d^{\beta}}{\left[d^2 + \left(h/\alpha\right)^2\right]^{\beta/2}} \quad \left(\alpha = 1,\ \beta = 2.3\right) \tag{5}$$

Combining the dimensionless coefficient with the elasticity equation (1), the elasticity equation can be written as matrix equations:

$$\begin{bmatrix} \boldsymbol{A}_{\mathrm{nn}}G & \boldsymbol{A}_{\mathrm{ns}}G \\ \boldsymbol{A}_{\mathrm{sn}}G & \boldsymbol{A}_{\mathrm{ss}}G \end{bmatrix}\begin{bmatrix} \boldsymbol{u}_{\mathrm{n}} \\ \boldsymbol{u}_{\mathrm{s}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\sigma}_{\mathrm{n}} \\ \boldsymbol{\sigma}_{\mathrm{s}} \end{bmatrix} \tag{6}$$

where the fracture height h is calculated by the enhanced equilibrium height model presented by Dontsov[16]:

$$p = \Delta\sigma\left(1 + \sqrt{\frac{2}{\pi h_{\mathrm{r}}}}\frac{K_{\mathrm{IC}} + \Delta K_{\mathrm{IC}}}{\Delta\sigma}\sqrt{\frac{h_{\mathrm{r}}}{h}} - \frac{2}{\pi}\arcsin\frac{h_{\mathrm{r}}}{h}\right) \tag{7}$$

$$\Delta K_{\mathrm{IC}} = 0.175^{1/6}(12\mu)^{1/3}\left(\frac{E}{1-\upsilon^2}\right)^{2/3} \times \left(\frac{1}{2}\frac{h_j - h_{j-1}}{t_j - t_{j-1}}\right)^{1/3} h_j^{1/6}\left(1 + 0.5\frac{h_{\mathrm{r}}\Delta\sigma}{h_j^{1/2}\Delta K_{\mathrm{IC}}}\right)^{-1/6} \tag{8}$$

Newton iteration method is used to solve the equilibrium height model (Eqs. 7 and 8).

1.2. Flow equations

The average width of hydraulic fractures is typically defined as:

$$w_{\mathrm{a}} = \frac{wh}{h_{\mathrm{r}}} \tag{9}$$

The average flow of fracturing fluid is expressed as follows:

$$q_{\mathrm{a}} = -\frac{w^3 h}{12\mu h_{\mathrm{r}}}\frac{\partial p}{\partial L} \tag{10}$$

With the average width and average flow, the conservation equation can be written as:

$$\frac{\partial w_{\mathrm{a}}}{\partial t} + \frac{\partial q_{\mathrm{a}}}{\partial L} = \frac{Q\delta}{d_1 h} \tag{11}$$

Combining equations (9-10) into equation (11), the conservation equation (11) is discretized by finite volume scheme:

$$w_{j+1} - w_j = \Delta t\left[B(w)p_i\right] + \Delta t\frac{Q\delta}{d_1 h} \tag{12}$$

where

$$B(w)p_i = \frac{1}{12\mu d_1 h_i}\left(w^3_{i+\frac{1}{2}}h_{i+\frac{1}{2}}\frac{p_{i+1} - p_i}{d_1} - w^3_{i-\frac{1}{2}}h_{i-\frac{1}{2}}\frac{p_i - p_{i-1}}{d_1}\right) \tag{13}$$

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