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RESEARCH PAPER

Fracture propagation laws in staged hydraulic fracturing and their effects on fracture conductivities

BAO Jinqing[1, 2], LIU He[1, 2, *], ZHANG Guangming[1, 2], JIN Juan[1, 2], CHENG Wei[1, 2], LIU Jiandong[1, 2]

1. PetroChina Research Institute of Petroleum Exploration & Development, Beijing 100083, China;
2. Key Laboratory of Oil & Gas Production, China National Petroleum Corporation, Beijing 100083, China

Abstract: Completely taking into account the interferences between fractures as well as the friction effects on injection allocations, a fully coupled finite element method inherited from a verified one is proposed to discuss fracture propagation laws and analyze their impacts on fracture conductivities. Simulations show that although fractures have similar injection allocations that fluctuate around the allocation averaged by fractures, interferences between them lead to their different propagation rates and some fractures even stop propagating for a while. Shorter fractures generally have higher pressure and smaller pressure gradients than longer ones. The pressure differences between fractures result in long fractures having bottlenecking zones far away from the wellbore, and make them vulnerable to screen-out at the inlets and the bottlenecking zones. The effects of the propagation laws on fracture conductivities include: (1) the conductivities in short fractures are weakened by rapid proppant settlement in them; (2) long fractures may lost their conductivities due to screen-out near the wellbore; (3) the conductivities in long fractures decrease because of screen-out at the bottlenecking zones.

Key words: horizontal well; staged hydraulic fracturing; interference between fractures; fracture propagation; fracture conductivity

Introduction

With the rising development of unconventional resource in recent years[1], drilling in horizontal wells and staged hydraulic fracturing within are playing an increasingly important role in petroleum industry. There are strong interferences between fractures that simultaneously propagate in staged hydraulic fracturing, and the interferences lead to different fracture shapes and resultant different stimulation effects. Analysis of production log data shows that 30 percent or even more fractures have no productivity due to their insufficient conductivities[2]. Till now there is no clear understanding on fracture propagation laws in staged hydraulic fracturing in horizontal wells, and the mechanisms causing insufficient conductivities in some fractures are unclear. So there is no reliable basis for optimizing the design of staged hydraulic fracturing in horizontal wells. Therefore, it is of great engineering significance to investigate fracture propagation laws in staged hydraulic fracturing in horizontal wells as well as these laws' effects on fracture conductivity.

A lot of researches have been conducted to discuss simultaneous fracture propagations based on the displacement discontinuity method (a boundary element method[3]). Peirce and Bunger[4] simulated simultaneous propagations of hydraulic fractures, pointing out that uneven spacings between fractures in staged hydraulic fracturing are favorable to improving the global fracture conductivities. Lecampion et al[5] proposed a dimensionless parameter to tell the leading mechanisms that dominate injection allocations in staged hydraulic fracturing, where the effect of perforation frictions on injection allocation is taken into account. They investigated fracture propagation laws as well as injection allocation ones on the early stage of hydraulic fracturing, covering a variety of leading allocation mechanisms. It is shown in their investigation that some fractures have low injection allocations and stop propagating if perforations cannot supply enough frictions. Kresse et al.[6] simulated simultaneous fracture propagations using an improved displacement discontinuity method, and discovered that side fractures play a dominant role. Sesetty et al.[7] investigated the effects of pre-existing hydraulic fractures on propagating ones, and pointed out that the boundary conditions arising from pre-existing fractures have strong effects on the shape of propagating ones. Xu et al.[8] discussed stress interference domains induced by multiple hydraulic fractures.

Many finite element methods have been proposed to simulate hydraulic fracturing in recent years. For the simulation of a single fracture, Hunsweck et al.[9] discussed the propagation of a hydraulic fracture with a fluid lag zone ignoring leak-off; Gordeliy et al.[10] simulated the propagation of a hydraulic

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*** Corresponding author.** E-mail: liuhe@petrochina.com.cn
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fracture under a variety of energy dissipation mechanisms and fluid lag situations with the extended finite element method; Bao et al.[11] investigated the propagation of a hydraulic fracture under various energy dissipation mechanisms and leak-off situations, and introduced a condensation technique to accelerate the simulation[12]. These numerical models are verified by some of the analytical solutions that are proposed in recent years in references [13−18]. For the simulation of multiple fractures, Dahi Taleghani[19] proposed an extended finite element method and found out that there is strong interference between fractures even when the fracture spacing is shorter than the fracture length; Zhang et al.[20] discussed the condition on the alteration of least principle stress direction when fractures simultaneously propagate in a reservoir based on the poro-elasticity theory; Pan et al.[21] examined the effect of stress interference on the simultaneous propagation of fractures based on damage mechanics.

Although there have been a lot of research efforts on simulating the simultaneous propagations of multiple fractures, the propagation laws of staged fractures and the origin of their insufficient conductivities have not been completely revealed. Further thorough investigation is still needed. Based on reference [11], here we propose a fully coupled finite element method to simulate staged hydraulic fracturing in horizontal wells, discuss their laws on fracture propagation rate, injection allocation, fracture width and fluid net pressure, and analyze these laws' effects on fracture conductivities. We hope that what we discovered can be served as a reliable basis for the optimization of staged hydraulic fracturing design in horizontal wells.

1. Physical and mathematical models

The mechanism of staged hydraulic fracturing in horizontal wells is that rock around the perforation clusters in a stage is expected to be fractured through injection allocation adjusted by frictions near the wellbore, where perforations in the clusters (Fig. 1a) are designed to produce the frictions when the allocated injection flows through them. The frictions are positively correlated to the allocation. It is generally assumed in numerical models that every cluster produces one fracture [4, 5, 19] in staged hydraulic fracturing. As shown in Fig. 1b, fractures are numbered 1 to N along the fluid flow direction in the wellbore, where N is the number of clusters in a stage. For simplicity, we assume that fracture propagates in a straight line perpendicular to the original least principle stress. Investigations[6, 7] show that this assumption is reasonable when the maximum stress is much larger than the least principle stress.

The equations that govern fracture propagations include those describing the fluid mass conservation in the stage, the relationship between fracture width and fluid pressure in fractures, pressure drops induced by frictions around and in the wellbore, and fluid mass conservation, fluid flow and leak-off in fractures. Ignoring the fluid compressibility and the wellbore radius, we put these equations based on a plain strain model where the fluid flow direction in the horizontal well is taken as the x axis in the Cartesian coordinates.

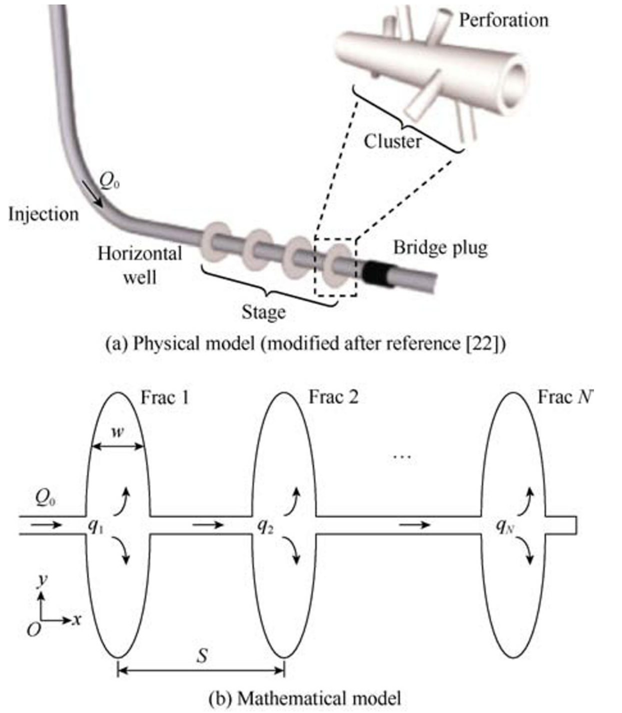

Fig. 1. Physical and mathematical models of staged hydraulic fracturing in a horizontal well.

As shown in Fig. 1b, the equation of fluid mass conservation in a stage is

$$Q_0 - \sum_{i=1}^{N} q_i = 0 \tag{1}$$

For a wellbore section between two neighbour fractures, the pressure drop induced by the frictions in the wellbore is

$$\Delta p_{i,\text{wb}} = p_{i,\text{wb}} - p_{i+1,\text{wb}} \tag{2}$$

For fluid in a fracture, its mass conservation equation is

$$\frac{\partial w}{\partial t} + \frac{\partial q}{\partial y} + g = 0 \tag{3}$$

where its flux near the wellbore is q_i/h . If the fluid is Newtonian, q is written as[23]

$$q = -\left(w^3/12\mu\right)\nabla p_\text{f} \tag{4}$$

where the gradient operator is defined in the fracture propagation direction. Carter's model [24] is used to simulate leak-off in the method, and it is written as:

$$g(y_1, t) = C_1/\sqrt{t - t_0(y_1)} \tag{5}$$

The pressure drop induced by the frictions around the wellbore is

$$\Delta p_i = \Delta p_{i,\text{p}} + \Delta p_{i,\text{t}} \tag{6}$$

where the experiment-fitted $\Delta p_{i,\text{p}}$ is[25]

$$\Delta p_{i,\text{p}} = \left(\frac{0.807\,249\rho_\text{f}}{n_i^2 d_i^4 c_i^2}\right) q_i^2 \tag{7}$$

The collected item in the bracket in Eq. (7) is the total perforation friction coefficient defined in reference [5].

According to references [26, 27], the generalized integral form of fracture width is