ARTICLE IN PRESS

Journal of Petroleum Science and Engineering xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Simulation of simultaneous propagation of multiple hydraulic fractures in horizontal wells

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ARTICLE INFO

Keywords:
Hydraulic fracturing
Numerical simulation
Displacement discontinuity method

ABSTRACT

The multi-stage hydraulic fracturing technology is widely used in horizontal wells for the economical production of fossil fuels. This technology can reduce the operational costs by simultaneously creating multiple hydraulic fractures, however production log data demonstrate its failure in generating effective hydraulic fractures from a portion of perforation clusters. In order to promote a more uniform fracture growth, we present a numerical model as a tool to investigate the simultaneous propagation of multiple hydraulic fractures in horizontal wells. The model captures related physical processes by coupling elastic deformation of rock, stress interaction among fractures, fluid flow in fractures and flow distribution into different fractures. We simulate the growth of multiple hydraulic fractures in numerical cases to investigate the competition process in hydraulic fractures. Numerical results indicate that some measures such as increasing perforation friction and utilizing the inter-well stress interference can promote the uniform growth of multiple hydraulic fractures. We also investigate these optimization measures and their limitation in engineering practice. Although some factors in practice, such as unpredictable near-wellbore tortuosity pressure drops, hinder the optimization of uniform growth, the above-mentioned measures are still proposed to partially mitigate the non-uniformity.

1. Introduction

At present time, hydraulic fracturing of horizontal well is a critical technology for extracting fossil fuels in reservoir by injecting pressurized fluid into rock to form hydraulic fractures (King, 2010). In order to meet fuel needs with cost savings, the horizontal well is often stimulated in stages, and multiple hydraulic fractures simultaneously propagate from several perforation clusters in a pumping operation. The multi-stage fracturing indeed improves the efficiency of operation. However, the corresponding production log data show that a part of perforation clusters are not well-contributed to the production, since approximately 80% of production comes from only 20% of perforation clusters (Miller et al., 2011). Non-uniformly distributed production implies a possible uneven growth of multiple fractures in horizontal well. Therefore, the physical processes of simultaneous propagation of multiple hydraulic fractures should be carefully investigated to increase the production in wells.

The problem of multiple growing hydraulic fractures is a very complicated process to model by proper coupling, as it includes the rock deformation induced by the pressurized fluid, the viscous fluid flow within the narrow fracture, the interference between fractures, and the dynamical flow distribution form wellbore into different fractures. Therefore, it is difficult to carry out numerical studies without some necessary simplifying assumptions. In many previous simulation study (Witherspoon et al., 1980; Klimczak et al., 2010), it is typically assumed that fluid flow within fracture is conceptualized as laminar flow between parallel plates (Poiseuille flow). In addition, it is usually assumed that the leak-off is one-dimension (Carter model). In practice, the fracturing fluid not only simply flows through the fracture, but also through the porous rock around fracture (Pascal, 1991; Pearson and Tardy, 2002; Longo and Federico, 2015; Yao et al., 2015). Since fracturing fluid flow is profoundly relevant to the process of fracture propagation, the assumptions of Poiseuille flow and Carter leak-off undoubtedly reduce the accuracy of numerical simulation. However, considering the multi-stage hydraulic fracturing mainly applies in unconventional reservoir, these assumptions are acceptable in macro-scale numerical model because the nearly impermeable rock.

Several previous researches (e.g. Olson, 2008; Roussel and Sharma, 2011a, 2011b; Morrill et al., 2012; Wu and Olson, 2015; Peirce and Bunger, 2015) focused on the multi-fractures problem indicate that, the invalidity of some hydraulic fractures is partly due to a phenomenon well-known as stress shadowing – a term used to describe

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http://dx.doi.org/10.1016/j.petrol.2016.09.021
Received 29 February 2016; Received in revised form 6 July 2016; Accepted 13 September 2016
Available online xxxx

inhibition of hydraulic fracture by compressive stresses of neighboring fractures (e.g. Germanovich and Astakhov, 2004; East et al., 2011; Nagel et al., 2011). In order to reduce the invalid hydraulic fractures, negative effects of stress interaction among hydraulic fractures should be minimized or counteracted by proper measures. Lately, Peirce and Bunger (2015) has carried out a study of numerical simulations by planar hydraulic fractures model and shown that the specified non-uniformly distributed perforation clusters can promote the uniform growth of multiple fractures. Just as the study implies, at present some critical mechanisms in the complex process deserve further investigation for the potential of improving uniform growth, such as the perforation pressure losses. In addition, previous researches mostly focus on the process in single well. In fact when multi-well fracturing technology like Simul-frac is carried out, inter-well interference may also benefit to achieve more uniform distribution of fractured surface.

In this study, our aim is to investigate some process of simultaneously growing hydraulic fractures to enhance understanding of the robustness of propagating multiple hydraulic fractures. Potential measures for promoting the uniform growth of multiple fractures, such as utilizing the inter-well interference, are also investigated. We present a numerical model that captures relevant physical mechanisms as a tool for this research. The non-planar hydraulic fracture model couples the elasto-hydrodynamic, stress interaction, fracture mechanics and the flux partitioning into different fractures in high computational efficiency. Comparing to some previous models that based on local elasticity (e.g. Xu et al., 2009; Kresse et al., 2011; Meyer and Bazan, 2011), this model includes non-local elasticity equations of displacement discontinuity method based on the study of Olson (2008) to accurately estimate the stress interaction. Meanwhile, the model further features a modified dimensionless factor to correct three-dimensional stress interaction.

The paper is organized as follows. First we describe the governing equations of the numerical model with corresponding simplifying assumptions. Then we simulate the simultaneous propagation of multiple hydraulic fractures to better understand the process among fractures by using the described numerical model. After that we investigate the measures which can improve the uniformity of growing multiple hydraulic fractures. Finally we discuss possible problems of the optimization measures in engineering practice.

2. The numerical model

2.1. Simplifying assumptions

The issue of multiple fluid-driven growing fractures comprises several physical processes such as deformation of the rock, fracture propagation, stress interaction, fluid flow in fracture and flux distribution in the wellbore. These growing hydraulic fractures start to markedly influence each other when their sizes reach near perforation cluster spacing (normally 10–30 m), usually after just tens of seconds propagation.

In order to effectively model the process for the research aim, some needed assumptions are typically made as LEFM (the fracture will propagate when the stress intensity factor at the fracture tip exceeds the rock toughness) and Poiseuille flow. The rock and in situ stress are assumed to be homogeneous (Young's modulus E, Poisson's ratio υ and toughness K_{IC} are uniform). The reservoir layer is surrounded by stress barriers imposed additional confining stress $\Delta\sigma$. The fracturing fluid is

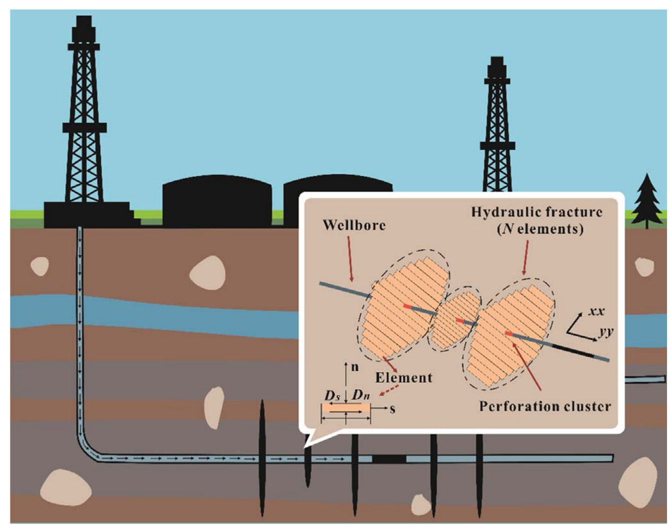

Fig. 1. Schematic of fracture model by displacement discontinuity method. Complex fracture geometries are constructed using N boundary elements.

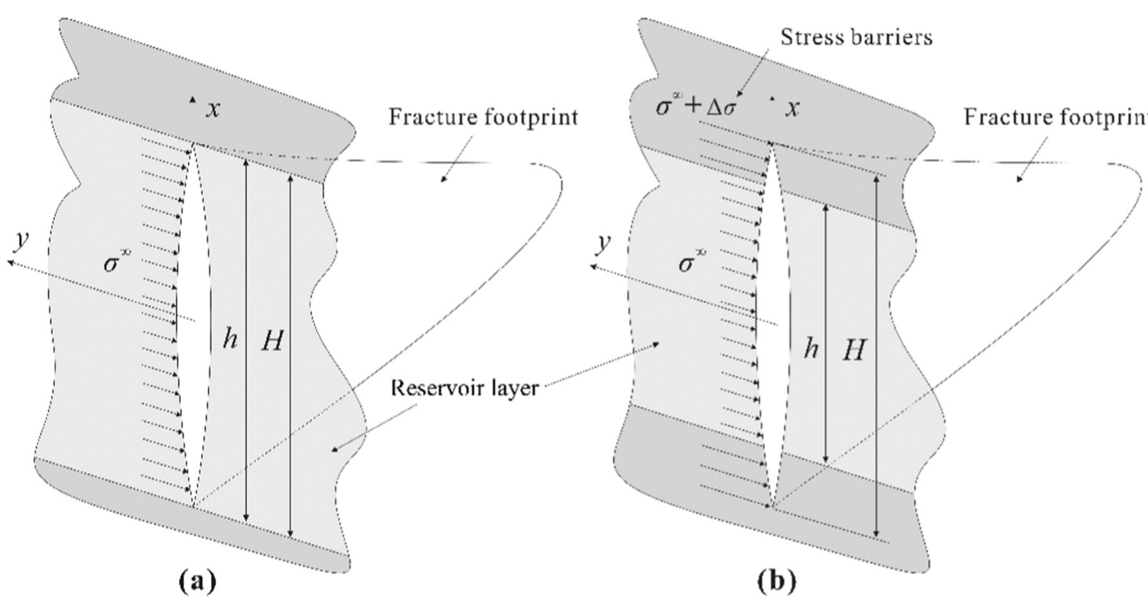

Fig. 2. (a) Hydraulic fracture is confined in reservoir layer with uniform loaded; (b) Hydraulic fracture extends into adjacent layers with non-uniform loaded.