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Numerical investigation for simultaneous growth of hydraulic fractures in multiple horizontal wells

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ABSTRACT

Recently developed multi-well fracturing technologies are widely used in unconventional low-permeable reservoirs for enhancing production. In this paper, we have implemented a three-dimensional numerical model, which couples the rock deformation, fluid flow and the dynamical flux partition in multiple wellbores, to simulate the simultaneous growths of hydraulic fractures in multi-well fracturing at unconventional reservoirs. To resolve the fully-coupled problem, a numerical scheme with four-layer loops is adopted in this model. The numerical simulations reveal that the asymmetric fracture propagations occur in multi-well fracturing, and the lateral growths of interior fractures are suppressed due to the intense inter-well stress interference. Results show that higher inlet pressure loss, achieved by limited entry design, is able to promote the lateral propagation of interior fractures. Then, case studies are performed to investigate the influences of fracture spacing, well spacing and fracturing scheme on fracture growths in multi-well fracturing. The results reveal that, when decreasing fracture spacing to a certain degree, the fracturing efficiency will not be promoted further by increasing fracture number. The case studies also indicate that, for successful fracturing treatment, a possible lower limit of well spacing should be considered in design, to avoid a sharp reduction of effectiveness in treatment. Compared to simultaneous fracturing scheme, study results show that zipper fracturing scheme has a better performance in promoting the fracture complexity and increasing the fracture surface area, which is favorable to enhance hydrocarbon production.

1. Introduction

Hydraulic fractures are a sort of tensile cracks in solid driven by injection of pressurized fluid. These tensile fractures often exist in natural environment as vertical magmatic dikes (Roper and Lister, 2005) or horizontal sills (Bunger and Cruden, 2011). In gas industry, man-made hydraulic fractures induced by viscous slurry are commonly used to promote the migration of natural gas in reservoirs and increase the gas production (Economides and Nolte, 2000). In recent years, multi-well hydraulic fracturing techniques such as simultaneous fracturing and zipper fracturing grow up to more efficiently stimulate unconventional low-permeable reservoirs (e.g. shale gas reservoir and tight gas reservoir). By carrying out fracturing operations concurrently at multiple horizontal wells (Fig. 1), these new techniques can significantly improve efficiency and cut down expenses in operations. In addition to saving cost, some numerical studies (e.g. King, 2010; Nagel et al., 2014) indicate that multi-well hydraulic fracturing is also beneficial to the improvement of production performance because the stress interferences may cause more complex fracture growth pattern and hence increase the stimulated reservoir volume (SRV). In practice, however, operators find that it is difficult to control stable growths of all hydraulic fractures when utilizing multi-well fracturing techniques. The failure of stable simultaneous growths of hydraulic fractures is partly due to the serious fracture interaction, known as stress shadowing (e.g. Nagel and Sanchez-Nagel, 2011; Germanovich and Astakhov, 2004; East et al., 2011). Due to the stress shadowing, part predominant hydraulic fractures often obtain more injected fluid and rapidly propagate, meanwhile some fractures gradually slow down their growth with getting less and less fluid. As a result, a portion of perforation clusters are non-productive after well-completion, leading to undesired cost-wasting (Miller et al., 2011). This has motivated the investigation on fracture growths in multi-well fracturing, to better understand how these growing fractures interact and help improve fracturing effectivity.

There has been a lot of numerical studies related to the simultaneous growth of hydraulic fractures (e.g. Olson, 2008; Roussel and Sharma, 2011; Morrill and Miskimins, 2012; Lecampion and Desroches, 2015; Wu and Olson, 2015; Zhao et al., 2016). These previous studies,

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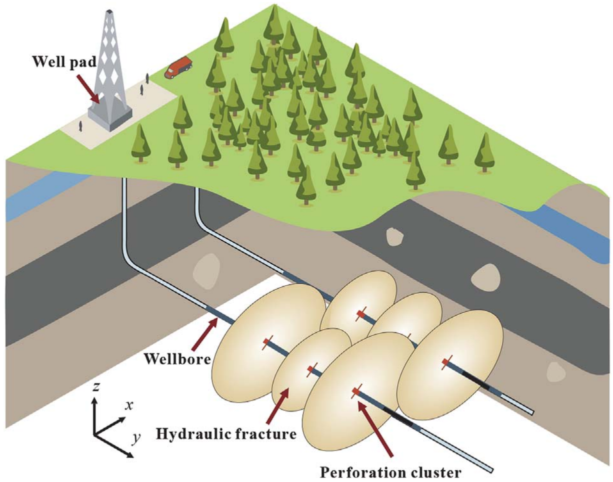

Fig. 1. A diagram of multi-well fracturing at two parallel horizontal wells. Multiple hydraulic fractures are simultaneously or alternately propagating at two wells.

however, mostly focus on the stress interaction between multiple fractures which initiate from the single well, and thus the influence of inter-well interaction is not considered. In the case of multi-well fracturing, inter-well stress interference will play a critical role to affect the fracture growths, and therefore it is necessary to investigate its mechanism in this situation.

With increasing attention to the inter-well stress interference, in recent years several researchers start to study the fracture growths in multi-well fracturing. Some previous studies have calculated the post-frac stress field, and predicted that the variations of fracture spacing and fracturing scheme may create more complex fractures by reducing the stress contrast in some area (e.g. Rafiee et al., 2012; Rios et al., 2013). Sesetty and Ghassemi (2016) has performed a 2D coupled model to investigate the multi-well fracturing in anisotropic rocks and indicated that zipper fracturing scheme is proposed to generate long and closely-spaced hydraulic fractures. Wu et al. (2017) has also implemented a 2D model to study the fracture geometry in two wells and found that increasing fracture spacing can effectively mitigate the fracture interaction. Recently, Li and Zhang (2017) has established a 2D XFEM model to study the multi-well fracturing treatments with considering the influence of natural fractures. The study reveals that the influence of stress perturbation on natural fractures varies based on their relative position to the created SRV.

The modeling of 3D multiple fracture growths is a challenge since it is hard to locate the moving fracture fronts. Thus, in many previous related studies, hydraulic fractures are typically assumed to be 2D or radial for simplification, although the assumption of specified fracture geometry will hinder the applicability of numerical results. For conveniently locating the moving fracture fronts in 3D model, Peirce and Detournay (2008) has introduced the implicit level set method (ILSM), by combining the fast marching method and tip asymptotic solution. Via using the ILSM, numerical investigations of multiple fluid-driven fracture growths in single horizontal well have been performed previously (Bunger and Peirce, 2014; Peirce and Bunger, 2015).

In this paper, our study aim is to further investigate the simultaneous growth of fractures in multiple well case (well pad), by a more realistic 3D numerical model. Via adopting the implicit level set method proposed by Peirce and Detournay (2008), we have implemented a solid-fluid coupled 3D numerical model, which is suitable for the cases of multi-well fracturing in unconventional low-permeable reservoir, to simulate the fracture growths. This paper is organized as follows. We firstly present the governing equations of this model with adopted simplifying assumptions. Then we test the validation of numerical model by comparing the numerical solution with analytical solution. In the following, numerical simulations are implemented to study the simultaneous fracture growths in multi-well fracturing. Case studies are performed to investigate respectively the influences of fracture spacing, well spacing and fracturing scheme on hydraulic fracture growths.

2. The numerical model

2.1. Assumptions

In order to improve computational efficiency of the numerical model, we adopt some typical assumptions to simplify the model. The model is assumed that:

1) Horizontal wellbores are positioned in parallel to each other, oriented in the direction of the minimum horizontal in situ stress (y-direction defined as Fig. 1). These hydraulic fractures are assumed to be transverse to wellbore.
2) The reservoir rock is homogeneous elastic medium. The fractures are considered as mode I cracks, and the fracture growth is governed by linear elastic fracture mechanics (hydraulic fracture grows when stress intensity factor K exceeds the rock toughness K_{IC}).
3) The injected fracturing fluid is considered as incompressible Newtonian. The fluid flowing within narrow fractures obeys Poiseuille's law.
4) The fluid leak-off is neglected in this study. This assumption is acceptable because, in typical unconventional reservoirs such as shale gas reservoir and tight gas reservoir (permeability $k < 0.1$mD), the rock is highly impermeable.
5) The fluid front is assumed to be coincided with the fracture front, hence there is no lag between fluid front and fracture front. This assumption is reasonable because the lag is no larger than a few centimeters at depths of thousands of meters, in typical conditions (Detournay, 2016).

In this model, it is possible to relax the assumption (1) that horizontal wellbores are oriented in the direction of the minimum horizontal stress. However, no matter the wellbores orientations are, the multiple fractures are still required to be assumed in plane along with the direction of maximum horizontal stress for simplification. This is because, properly simulating a complex 3D near-wellbore tortuosity of hydraulic fracture is a difficult task at present, as it requires a criterion to accurately capture some mixed-mode cracks pattern such as II-III mode (a combination of sliding and tearing fracture), which has not been successfully developed yet.

In addition, the assumption (4) that leak-off is neglected can be relaxed by introducing the Carter leak-off model, if demand is there (e.g. rock permeability $k \gg 0.1$mD). Although the Carter's model assumes the fluid leak-off into the porous rock is one-dimensional, it can be applied in simulating hydraulic fracturing because the injection time is relatively short. However, the Carter leak-off model is not applicable for simulating long-time injection operation such as waterflooding in reservoir.

In spite of using these assumptions, the simplified governing equations can still capture dominant processes (rock deformation, fluid viscous dissipation, fracture interaction and dynamical inlet fluid partition) during the multi-well fracturing treatment. The fully solid-fluid coupled model is enough to provide applicable insight for our limited study aim.

2.2. Rock deformation

The 3D version of displacement discontinuity method (Crouch, 1976; Crouch et al., 1983) is adopted to calculate the fracture aperture (fracture widths). The elasticity equations can be written as an integral equation of the form: