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The role of stress interference in hydraulic fracturing of horizontal wells

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ABSTRACT

One of the newly introduced fracturing designs is Texas Two-step, which still requires to be studied in depth, in particular, the impacts of stress shadowing and parameters involved for a more effective fracturing job. In this work, a poro-elasto-plastic computational model for 2-D hydraulic fracture propagation simulation is presented. The Cohesive Crack Model (CCM) is employed for modeling fracture propagation and represents inelastic behavior ahead of fracture tip. On the other hand, the rock formation in the entire simulation domain is modelled by the elasto-plastic constitutive equations of the Drucker-Prager model. The solution accounts for fracture initiation and propagation, coupling between elastic deformation and fluid flow within the hydraulic fractures, stress interactions between induced fractures (stress shadowing effect). This study also takes into account the presence of a local pressure drop in a perforation by considering a specific type of pore pressure element, called Perforation Entry Element (PEE), in the model. The crucial contribution of the present work is to investigate the influences of stress shadowing and In-situ Stress Ratio (ISR) on the propagation path of the fractures in both Texas two-step and Sim-HF designs. It has been concluded that design of the actual Fracture Spacing (FS) of the first two fractures in Texas two-step is of highly importance so as to ensure adequate degree of interference without the concern of generating so much induced stress such that the middle fracture propagation is restricted.

1. Introduction

Multi-stage Hydraulic Fracturing (HF) and horizontal wellbore drilling technologies are playing a crucial role in boosting U.S. natural gas production from 24.1 trillion cubic feet in 2012–37.5 trillion cubic feet in 2040, a 56% growth.[1] Because of the success accomplished by using HF, the industry highly attempts to develop the cutting edge and innovative technologies and their field applications. Notable advancement has been made in well completions to accommodate well-stimulation treatments and enhance HF efficiency and cost-effectiveness. These encompass multi-stage HF completions, both openhole and cased; disintegrating dropdown isolation balls and in-tubing plugs.[2,3]

The numerical modeling of HF, as a multi-physics problem which involves several range of physical concepts including poro-mechanics, fluid mechanics, and fracture mechanics, has drawn a particular attention in recent years. The most widely distinguished numerical techniques for the modelisation of HF include Boundary Element Method (BEM),[4] Displacement Discontinuity Method (DDM),[5–7] Discrete Element Method (DEM),[8,9] FEM,[10–15] Peridynamics,[16–19] XFEM,[20–23] and Cohesive Phantom Node Method (CPNM).[24,25] Among them, peridynamics based on the non-local theory of continuum mechanics has presented promising results for the HF problem. The essence of the peridynamics introduced by Silling[26] is that integration, instead of differentiation, is employed to determine the force at a material point. Is spite of the advantages of the peridynamics theory for solid and fracture mechanics demonstrated in,[27–29] this theory has not been fully implemented in the numerical modeling of HF. The main works in this area can be referred to works by Ouchi et al.,[16–18] and the first doctorate dissertation in this topic by Ouchi.[30] One of the main disadvantage of the peridynamics to mention is highly computational expenses of this technique. It is worth noting that in most available literature dedicated to numerical modeling of HF,[31–34,24,25,35,36] it is supposed that total fluid injection rate for each perforation is prescribed in an HF job, nevertheless, the flow rate of fracturing fluid into a perforation should be determined by taking the perforation entry friction into consideration.[37,38] In the present study, a specific type of pore pressure element, called Perforation Entry Element (PEE), is proposed to model the local pressure drop within the perforation.

In order to decrease operational cost of HF treatment, Simultaneously HF (Sim-HF) has been prevalent in the oil and gas industry. In this completion design, multiple clusters are stimulated at once so that multiple fractures are potentially initiated and propagated together. Although Sim-HF represents its potential as a major cost savings job, filed data of production logs over several basins shows that

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between 20% and 30% of perforations might not contribute to production.[39] A probability is that the process of simultaneously growth of multiple fractures placed near to one another inevitably results in preferential propagation of some fractures. When multiple fractures are situated close enough together, stress interference effects among them, which is known as stress shadowing,[40] take place that are not accounted for an individual hydraulic fracture calculations. Stress shadowing effects are potentially crucial to the design of multiple clusters HF, thus, multiple HF treatment should not be designed identical to a single HF simulation. [41]

A deep understanding of the stress shadowing leads to reduce the risk to the cost and profitability of multi-stage HF. To achieve a more-effective completion design with higher Estimated Ultimate Recovery (EUR), a completion engineer should weigh both advantages and disadvantages of stress shadowing in multi-stage HF. On one hand, stress shadowing enhances the fracture complexity as a consequence of lessening the stress anisotropy adjacent to closely spaced induced fractures. The reduction in the stress anisotropy activates not only natural fractures but also un-propped fractures in the shale reservoirs.[42] The latter ones include micro-fractures resulting from the slippage along planes of weakness such as bedding planes, and the slippage of pre-existing natural faults or fissures. Accordingly, the complex fracture network generated as a result of stress shadowing is the major contributory factor in creating larger fracture-surface area and greater fracture complexity in some shale reservoirs. Wang et al.[9] showed that the hydraulic fracture geometry changes from a bi-wing fracture to a complex fracture network owing to a decline in the stress anisotropy. On the other hand, the stress shadowing rises drastically in HF with closely spaced perforations, and consequently, the propagation of some fractures suppresses the propagation of the others.

Thanks to striking advancement in science and technology for developing mechanical systems for performing completions, more sophisticated designs have been introduced to generate optimal complex network of fractures. Conventional completion design to facilitate creation of secondary fractures is the Sim-HF as described earlier. As multiple fractures grow at the same time, the stress shadowing generated alters the horizontal stress contrast in the reservoir around each fracture, resulting in opening natural fractures. While this operation has been widely approved, the degree of effectiveness is suspect mainly due to fact that middle fracture in a three-interval treatment, is unproductive, as explained before. Soliman et al.[43,44] proposed an alterative technique, named Texas two-step, to conventional fracturing in order to enhance the far-field fracturing complexity in the reservoir. The Texas two-step is analogous to a popular dance associated with country-and-western music: two steps forward, one step back. Initiating the fracturing job from the toe of the horizontal well, the first perforation is stimulated, afterwards moving toward the heel, a second perforation is stimulated such that there exists a degree of stress shadowing between two induced fractures. Then, rather than continuing toward the heel, the third perforation is fractured between the two previously fractured perforations to take advantage of the stress shadowing in the rock and activation of the un-propped fractures to induce far more fracture complexity. In addition, as the middle fracture propagates, the shear stress near the tips of the fractures changes significantly, emitting shear waives which is captured by microseismic receivers. Although the Texas two-step looks promising in the sense of generating a complex network of fractures, it still requires a deeper investigation and understanding of the influence of stress shadowing and parameters involved for a more effective fracturing job. Roussel and Sharma[32] and Manchanda and Sharma[31] demonstrated that Texas two-step compared with conventional simultaneous fracturing reduces the effective Fracture Spacing (FS) in a horizontal wellbore and results in more-efficient completions. Moreover, they purported that a stress reversal region adjacent the induced fracture, with stress re-orientation of 90 degrees, occurs. This region imposes a confining condition on the fracture spacing which should be large enough to avoid the initiation of longitudinal fractures. However, this hypothesis seems to be questionable. It is mainly because the methodology applied in that paper ignores curving fracture paths.[25]

Unlike previous studies,[45–47] in the present work, on one hand, the Cohesive Crack Model (CCM) is used for modeling fracture propagation and represents inelastic behavior ahead of the fracture tip. On the other hand, the rock medium in the entire simulation domain is considered using the elasto-plastic constitutive equations of the Drucker-Prager model. Inspired by the lack of an effective numerical technique in the available literature, the Cohesive segments method in combination with Phantom Node Method, termed CPNM,[24,25] is established in this paper, being capable of not only simulating curving hydraulic fracture propagation with a solution-dependent path, but also undertaking the practicable emergence of multiple cohesive cracks within a porous formation. In addition, very few works[31,32] have been concentrated on the Texas two-step design. That is why besides the Sim-HF, this paper is specially dedicated to investigation of the impacts of stress shadowing and parameters involved in Texas two-step design for a more effective fracturing job.

2. Problem statement

The simulation of the initiation and propagation of hydraulic fractures from a horizontal well is a substantially complex problem. This problem includes deformation of the solid phase subjected to the fluid pressure on the fracture surfaces, fluid flow throughout the porous medium, flow of the fracturing fluid through the fracture, fracturing fluid infiltration from the fracture into the formation. Fig. 1 shows a schematic representation of the hydraulically fluid-driven fracture problem considered in this study. A 2-D domain Ω surrounded by the external boundary Γ is presupposed. The boundary Γ is subjected to the prescribed displacement $\bar{\mathbf{u}}$ on Γ_u, prescribed fluid pressure p on Γ_p, and the prescribed traction $\mathbf{t}$ on Γ_t. The domain includes an internal hydraulic fracture interface Γ_f which is imposed to the injection of an incompressible Newtonian viscous fluid. It is worth noting that the internal interface of the fracture undergoes three distinct mechanical

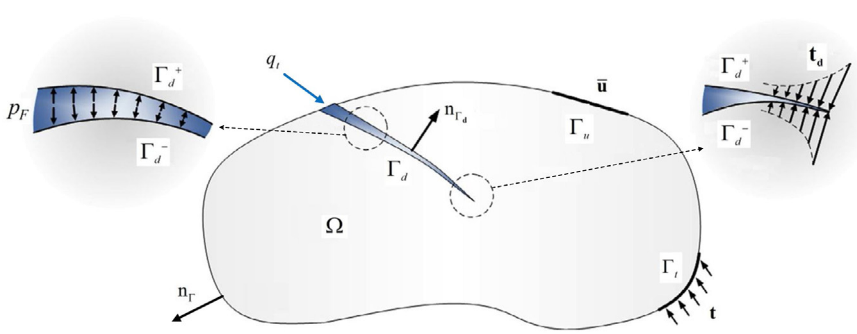

Fig. 1. A Schematic view of hydraulic fracture problem and associated boundary conditions.