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Pore pressure and stress coupling in closely-spaced hydraulic fracturing designs on adjacent horizontal wellbores

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ABSTRACT

Significant advancement in developing mechanical systems in oil and gas industry has paved the way for introducing more sophisticated completion design. Recently, new fracturing designs in neighboring lateral wells have been introduced to enhance the production of trapped hydrocarbons, in particular in low-permeable shale reservoirs. The new designs aim at mitigating side-effects of stress shadowing whereas enhance the far-field fracture complexity. The present paper concentrates on the numerical simulation of the various fracturing design on adjacent lateral wells including Simultaneously Hydraulic Fracturing (Sim-HF), Sequentially Hydraulic Fracturing (Seq-HF), Modified Zipper-Frac (MZF), and Modified MZF (M2ZF). In this study, the Cohesive segments method in combination with Phantom Node Method, termed CPNM, is established to simulate the initiation and propagation of multiple fractures along arbitrary, solution-dependent paths. The proposed CPNM is capable of simulating curving hydraulic fracture propagation for studying the stress shadow effects resulted from pre-existing/simultaneous induced fractures. As opposed to original MZF, the stress shadow effects in the M2ZF are managed through non-uniform fracture spacing. The advantages and disadvantages of the stress shadowing effects, as a function of fracture spacing, on the fracture propagation path, pore pressure of the formation, the horizontal-stress contrast, and the in-plane shear stress have been studied in detail. It has been inferred that the operation time between consecutive stages in MZF design plays a crucial role in the closure of the un-propped fractures and, as a result, in the production performance of the wellbores.

1. Introduction

Unconventional reservoirs, especially shale gas, have emerged as a promising contributor to the global energy demand. After successful production from the Barnett Shale in central Texas, the U.S. has developed several other shale plays, including the Marcellus, Haynesville and Eagle Ford shales, followed by great interest in other parts of the world, such as Canada, Australia, Poland, China. According to Energy Information Administration (EIA) (U.S. Energy Information Administration (EIA), 2013), it is projected that 50 percent of the total natural gas production in U.S. by 2040 is allocated to the shale gas, which is also more environmentally friendly than other conventional fossil fuels. Owing to low permeability of the shale reservoirs, the combined use of hydraulic fracturing and advanced horizontal drilling techniques plays a crucial role in unlocking those plays and achieving economic production rates.

Recently, developments in oil and industry have evolved significantly in progressing and flourishing mechanical systems to perform hydraulic fracture jobs, whereas the considerable achievement in the hydraulic fracturing design demands a more deep understanding of the impacts of a wide variety of design elements. One of the indispensable factors in multi-stage hydraulic fracturing design is "stress shadowing" or "altered-stress", which is regarded as stresses interference among multiple fractures placed closely on an individual or multi-wellbores. A thorough grasp of stress shadowing brings remarkable advantages with regard to risk alleviation on the cost and profitability of multiple fracturing treatment. To accomplish a successful fracturing job with higher drainage area, a completion engineer should weigh both pros and cons of stress shadowing in multi-stage hydraulic fracturing. On

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one hand, stress shadowing increases the fracture complexity as a result of reducing the horizontal-stress contrast in the vicinity of closely spaced induced fractures. These zones of low stress anisotropy are far more contributory to the opening of natural fractures and can result in better connectivity with a natural-fracture network. On the other hand, the stress shadowing effect increases dramatically in completion design with closely spaced perforations and, as a result, the growth of some fractures suppresses the propagating of the others.

Based on the results obtained by Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS), Sookprasong et al. (2014) concluded that the dominant perforation clusters are often recognized during simultaneously hydraulic fracturing. Furthermore, Spain et al. (2015) elaborated that in unconventional reservoirs, around 40 to 60 percent of perforation clusters are without production. Effects of stress shadowing on the various completion procedure from multi-lateral wellbores in the upper Barnett shale have performed by Vermylen and Zoback (2011) using microseismic events. The results revealed that considerable discrepancies between different completion resulted due to stress shadowing effects. A numerical evaluation of the impacts of stress shadowing on the multi-stage hydraulic fractures as a function of Fracture Spacing (FS) and in-situ stress ratio have been done by Nagel et al. (2011) without considering fluid leak-off. They obtained that with sequential fracturing, the second fracture, which grows under stress shadowing of initial fracture, exhibits very little associated natural fracture shearing. Roussel and Mukul (2011) employed a 3-D numerical method of stress interference for simultaneous and sequential fracturing. They analyzed a series of the numerical simulations and supposed that stress interference or reorientation rises by the number of fractures propagated and is dependent on the sequence of fracturing. Based on enhanced 2-D Displacement Discontinuity Method (DDM), Wu et al. (2012) investigated the stress shadowing effects in a complex hydraulic fracture network. The authors concluded that fractures can either enhance or repel each other depending on their initial spacing due to the impacts of stress shadowing. A 2-D coupled DDM for simulating fracture propagation in simultaneous and sequential hydraulic fracture operations for single and multi-wellbores was presented by Sesetty and Ghaessmi (2015). It was found that in simultaneous propagation of hydraulic fractures, the outer fractures dominate the growth of inner fractures. In addition, the center fractures usually stop after they reach a certain length due to the stress shadowing between them.

According to well-testing analysis and field observations, it has been evident that hydraulic fracture-surface area is far larger than that of assessed in conventional fracturing design. Such circumstance can be resulted from two factors. One emanates from the fact that vast majority of tight sand and shale reservoirs are naturally fractured, such as Barnett shale (Gale et al., 2007; Dahi Taleghani et al., 2013). Besides the presence of natural fractures, the other factor may be referred to the un-propped fractures (Sharma and Manchanda, 2015), which can be induced as a result of stress shadowing effect during the inducing the main propped fracture. The un-propped fractures encompass micro-fractures stemming from the slippage along planes of weakness such as bedding planes, and the slippage of pre-existing natural faults or fissures. Consequently, the complex network of un-propped fractures appear to be the primary reason explaining why some reservoirs demonstrate greater fracture complexity. A number of attempts (Meyer and Bazan, 2011; Nagel et al., 2011) have been made to explain the natural-fracture networks and their consequences on the induced fractures propagation. However, fundamental data on pre-existing networks are virtually out of the question to acquire. Wu and Pollard (2002) and Olsen et al. (2009) demonstrated that the width at the intersection of the hydraulically induced fracture and the natural fractures is dependent on several parameters such as the stress anisotropy. The reduction in the stress anisotropy can activate the Mode I opening of planes of weaknesses, resulting in generating complex network which links hydraulically induced fractures to pre-existing natural fractures. Thus, presence of substantial fracture surface area causes higher drainage of the low permeability reservoir and maximizing the Stimulated Reservoirs Volume (SRV). Weng and Siebrits (2007) demonstrated that the hydraulic fracture geometry changes from a bi-wing fracture to a complex network of fractures as a result of a reduction in horizontal stresses contrast.

In recent years, thanks to astonishing technology advancements, several sophisticated designs have been developed to generate optimal complex fracture networks. Among various completion designs, “Texas two-step” has been presented to reduce the FS and create greater fracture complexity (Soliman et al., 2010). According to this technique, after fluid injection into first interval, by moving towards the heel, a second interval is stimulated and, as a result, there is a degree of stress interference between the two fractures. Afterwards, rather than continuing towards the heel of the well, the third interval is stimulated between the two previously fractured intervals with the aim of altering the stress in the rock so as to contribute to the generation of secondary fractures. Using a finite difference and explicit numerical scheme, Roussel and Sharma (2011) and Manchanda and Sharma (2014) showed that lower FS can be achieved in the scenario of Texas two-step compared with conventional simultaneous fracturing. In addition, they purported that a stress reversal region, close to the main induced fracture, with stress re-orientation of 90° takes place. This zone imposes a confining condition on the FS which should be large enough to avoid the initiation of longitudinal fractures. Nevertheless, this hypothesis seems to be questionable because propagating of new fractures into the altered-stress region caused by the previous fracture can considerably change the local stresses, which will be discussed further in this paper.

Taking multi-lateral wellbores into account, based on the “Zipper-Frac” technique, two or more horizontal wellbores can be fractured simultaneously with the aim of augmenting stress perturbation close the tips of each fracture. Based on this method, when the opposite fractures move toward each other, to some extent the interference takes place ahead of fracture and enforce the fractures to propagate through the direction perpendicular to the horizontal wellbore. Based on continuum geomechanics, Rios et al. (2013) performed a stress shadow analysis and presented that the Zipper-Frac creates an extensive region of ascended normal stresses and descended shear stresses, which has the impact of stabilizing natural fractures and weakness planes instead of enhancing their shear. However, the application of Zipper-Frac is restricted because of two main deficiencies. Firstly, the creation of complex field is limited to the area close to the fractures tips. Secondly, it is associated with the risk of connection of adjacent wellbores if opposing fractures become very close. Motivated by the advantages of the presence of a middle fracture between two consecutive fractures used in Texas two-step, another method, known as “Modified Zipper-Frac” (MZF) (Soliman et al., 2010), involves fractures from two lateral wells situated in a staggered pattern. Rafiee et al. (2012) studied the advantages of the Zipper-Frac and the MZF by using analytical stress interference calculations around various fracture geometries. They showed that the MZF completion potentially increases the stress interference between the fractures and provides more fracture complexity compared with Zipper-Frac. However, this study did not consider the curving propagation of hydraulic fracture which plays crucial role in closely spaced fractures. By using a Discrete Element Method