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# Numerical and experimental investigation of the interaction of natural and propagated hydraulic fracture

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ABSTRACT

Hydraulic fracturing is extensively used to develop unconventional reservoirs, such as tight gas, shale gas and shale oil reservoirs. These reservoirs are often naturally fractured. Presence of these natural fractures can have beneficial or detrimental effects on the outcome of hydraulic fracturing operation. A proper study is required to characterize these formations, and design a suitable hydraulic fracturing operation.

This paper investigates the interaction of hydraulic and natural fractures based on numerical and experimental studies. Distinct Element Method (DEM) based numerical model has been used to simulate interaction of hydraulic and natural fractures; and the simulation results are validated through experimental studies. The experimental results are found to be in very good agreement with simulation results. The study demonstrated that the Distinct Element Method based numerical model can be used as an alternative to laboratory experiments to investigate the interaction mechanisms of hydraulic and natural fractures with greater confidence. Both experimental and numerical simulation tests showed that increasing the angle between plane of natural fracture, and direction of maximum horizontal stress increases the chance of hydraulic fracture to cross the natural fractures. At low angles, hydraulic fracture is most likely to be arrested at the plane of natural fracture; and/or cause a shear slippage at the plan of natural fracture. Natural fracture filling materials also have a great effect on the interaction mechanism. Weakly bonded natural fracture surfaces increase the chance of shear slippage to occur, and arrest the propagation of hydraulic fracture even at the high angle of interaction as high as 90°.

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## 1. Introduction

Hydraulic fracturing of oil and gas wells gained huge popularity since it was introduced by Stanoilind in 1949 (Montgomery and Smith, 2010). This technology is essentially important for the development of shale oil and shale gas reservoirs. Often these reservoirs are naturally fractured. This characteristic causes to branch out the propagated hydraulic fracture which can be either beneficial or be detrimental to the success of hydraulic fracturing operation depending on hydraulic fracture interacted with existing natural fracture. The branch out fractures that cause more reservoir area to be exposed to hydraulic fracture is generally beneficial. However, branch outs can cause early fracture slurry dehydration and premature proppant screen out that is detrimental to success of hydraulic fracturing operation. Proper study of interaction mechanism is thus essentially important for the efficient as well as effective design of hydraulic fracturing operation. Among the important parameters that can affect the interaction mechanism are principal stresses, fluid viscosity, flow rate, sizes of natural fractures and their orientation with respect to principal stresses, properties of fracture filling material and so on. Many researchers tried to solve this mystery either by laboratory experiments (Lamont and Jessen, 1963; Anderson, 1981; Hanson et al., 1981; Blanton, 1982, 1986; Shaffer et al., 1984; Warpinski and Teufel, 1987; Renshaw and Pollard, 1995; Zhou et al., 2008; Gu et al., 2011, 2012), field experiments (Johnson et al., 2010a, 2010b; Scott et al., 2010), analytical methods (Hanson et al., 1981; Blanton, 1982, 1986; Warpinski and Teufel, 1987; Renshaw and Pollard, 1995; Zhou et al., 2008; Gu et al., 2011, 2012; Daneshy, 1974; Thiercelin and Makkhyu, 2007; Gu and Weng, 2010) or numerical simulations (Shaffer et al., 1984; Thiercelin and Makkhyu, 2007; Nagel et al., 2012; Sesetty and Ghassemi, 2012; Chuprakov et al.,

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2013; Cottrell et al., 2013; Zhang et al., 2014; Wu and Olson, 2014; Dahi Taleghani and Olson, 2014; Wu and Olson, 2015). Analytical studies endeavour to capture the physics of the problem and try to solve it by applying mathematical models derived using physical laws. Such mathematical models are often complex, and very challenging to derive realistic analytical solutions, especially for porous heterogeneous formation in a dynamic condition. Consequently very often such solutions are oversimplified, which generally considers homogenous elastic medium in a static scenario; and assume the hydraulic fractures already intersected the natural fracture. However, the propagation of hydraulic fracture is a dynamic process that changes the state of stress within the rock as the fracture propagates. Fracture re-initiation may occur beyond the natural fracture or from its tips before hydraulic fracture intersects natural fracture. If the numerical solutions are based on these analytical derivations, it will suffer from the same problems. Experimental studies can be considered to be a better representation of real situation amongst different solutions. Samples can be prepared in custom mode to study the effect of different parameters on the interaction mechanism. However, these experiments are not only expensive but also extremely tedious and time consuming, which hardly efficient, especially for routine industry application. This puts constraint on the number of sensitivity analysis that can be conducted and subsequent conclusions that can be drawn. This shows that none of the aforementioned methods can be used separately. Normally limited experimental studies are conducted for the calibration of numerical or analytical models. After that, numerical and analytical models are used for further sensitivity analysis to capture a wider range of situations.

Raymond et al. (Johnson et al., 2010a, 2010b) and Scott et al. (2010) performed extensive analysis using field studies to understand fracture propagation in a coal seam gas reservoir in Queensland, Australia. They used advanced combination of petrophysical analysis to build the geomechanical model of the field and characterize presence, properties and orientation of natural fractures. They then used Gohfer software to design the hydraulic fracturing operation. Afterwards, they used a combination of radioactive tracers, sonic anisotropy logs, microseismic and tiltmeters to infer fracture initiation and propagation inside coal beds and their adjacent formations. Different monitoring systems showed consistent fracture height growth although some discrepancies between design and results as well as between results from different monitoring systems are observed. These discrepancies are well explained by them.

Wu et al. (Wu and Olson, 2014) developed a three dimensional model based on displacement discontinuity and finite element method. They considered constant fracture height; and removed the shear stress in the vertical direction. This simplified the model to be more like a 2D model (i.e. pseudo 3D). The problem of fluid flow and rock mechanical coupling was solved iteratively using Newton-Raphson and Picard iterative method. Zhang et al. (2014) developed a Discrete-Continuum model using PFC2d and Flac2d to investigate the interaction mechanism. They performed rigorous sensitivity analysis to study the effect of different parameters such as flow rate, fluid viscosity, material stiffness etc, on the interaction outcome. However, model results were not verified by other means such as experimental or analytical results. Keshavarzi and Jahanbakhshi (2013) studied the interaction mechanism using extended finite element method (XFEM). They used the concept of energy release rate for fracture propagation and fracture behaviour at intersection point in a 2D space. Their numerical results showed good agreement with Warpinski and Teufel's experimental results (Warpinski and Teufel, 1987). Dahi Taleghani and Olson (Dahi Taleghani and Olson, 2014) also used XFEM to investigate the interaction mechanism. Similar to Keshavarzi and jahanbakhshi, they used the energy release rate for intact rock and natural fracture to determine the interaction outcome. They used this model to investigate the propagation of hydraulic fracture in presence of abundant natural fractures under different stress regimes.

Dependence of most of the numerical models on analytical results makes them prone to same errors that are present in analytical results. Meshing requirement also makes these models rigid for fracture advancement. Re-meshing requirement in some of these models such as the ones that are dependent on finite element model creates another difficulty to use these models. The distinct element method presented in this paper is found to be unique in nature as it does not depend on analytical solutions that cover the hydraulic fracturing process. Fracturing occurs as a result of decoupling between sample particles. Model results have been validated through comparison with experimental results. These experiments were conducted in True Tri-axial Stress Cell (TTSC) with the capability to impose three independent stresses on the sample.

## 2. Numerical studies

Reservoir rock may contain imperfections such as faults, joints, natural fractures and so on. Simulating these rocks in Discrete Element Method (DEM) based numerical model is easier and more accurate than using a Continuum or Finite Element based numerical model. In DEM, sample is modelled as a composite of individual particles that can move and rotate with respect to each other. This

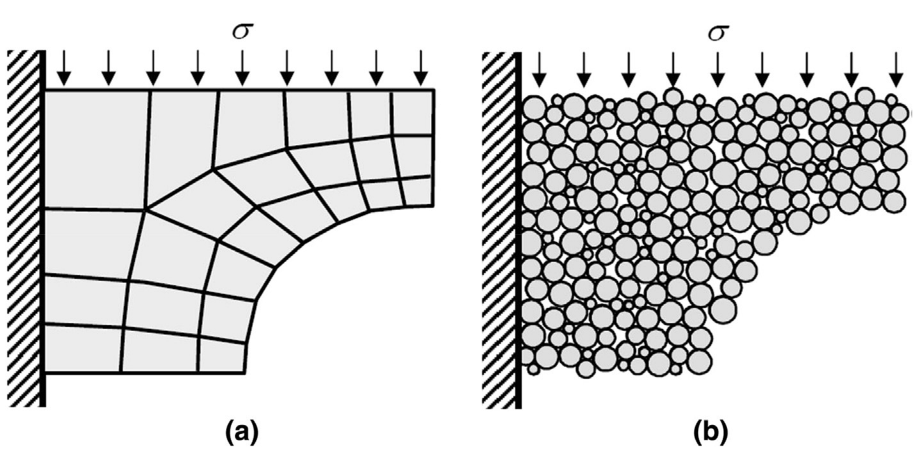


**Fig. 1.** Sample modelled using a- Finite Element Method (FEM). b- Discrete Element Method (DEM) (Tavarez, 2005).

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