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# A numerical study of sequential and simultaneous hydraulic fracturing in single and multi-lateral horizontal wells

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## ABSTRACT

Horizontal well hydraulic fracturing (HF) technology can help to develop low permeability oil and gas resources. Today, industry uses simultaneous and sequential fracturing as a means to fracture single or multiple (Zipper Frac) horizontal wells as an efficient way to produce oil/gas. In zipper fracturing two or more parallel wells are fractured simultaneously or sequentially to achieve the maximum stimulated reservoir volume. In order to achieve optimum stimulated rock volumes and fracture networks, one must understand the effect of various rock and fluid properties on stimulation to minimize the risk of unwanted fracture geometries. This paper describes the development and application of a 2D coupled displacement discontinuity numerical model for simulating fracture propagation in simultaneous and sequential hydraulic fracture operations for single and multiple parallel wells. The sequential fracturing model considers two different boundary conditions for the previously created fractures. A constant pressure boundary condition along the fracture surface is considered when the flow back is restricted between the stages and a joint model is used when fractures are propped. A series of examples are presented to study the effect of fracture spacing on expected stimulated zone. It is found that fracture path is not only affected by fracture spacing but also by the boundary conditions on the previously created fractures.

## 1. Introduction

Increased interest in exploration and production of low permeability reservoirs presents new challenges in design and evaluation of hydraulic stimulation treatment of horizontal wells. Each treatment stage in a well is designed to generate a stimulated volume with a desired permeability enhancement. The collective stimulated zones should affect the maximum volume with minimal overlap of adjacent treatment stages. Usually, HF treatment of horizontal wells is carried out using one of two schemes namely, Simul-Frac and Sequel-Frac. In simultaneous fracturing multiple cluster zones are treated so that multiple fractures are potentially created and propagated at the same time whereas in sequential fracturing, clusters are treated in series so fractures are created one after another, usually by keeping the previously created fracture either propped (Rodrigues et al., 2007) or pressurized with fluid (Soliman et al., 2008). Zipper fracturing is a technique where two or more lateral horizontal wells (usually at the same depth) are fractured simultaneously or sequentially. The main purpose of zipper fracturing is to create close fractures and maximize stimulation effect, thus improving the stimulated rock volume. In all cases, the perforation clusters should be placed such that competing stress-shadow effects between them is minimized. By reducing the number of clusters per stage, costs are reduced and stress interference is minimized, reducing the possibility of having ineffective fracturing.

Often, production forecasting analysis is used by assuming simple straight lined fractures to optimize spacing and staging between fractures, but in reality fractures tend to propagate in complex manner when they are closely spaced or where pre-existing fractures exist (Bunger et al., 2011). In simultaneous fracturing closely spaced clusters may cause fracture interferences such that some of the fractures stop in between, and some may not even initiate due to the stress shadow effects (El Rabba, 1989). Thus, design of efficient systems can benefit from hydraulic fracture simulations that couple fluid flow to fracture deformation and fracture mechanics principles. Numerical method that can accurately model 2D or 3D fracture propagation can help to understand and improve the fracturing process.

The growth of multiple simultaneous fractures assuming no fluid flow inside the fractures has been studied (Rafiee et al., 2012) and simulated the sequential fracturing has been treated with no explicit fluid. In (Bunger et al., 2011) previously created fractures in sequential fracturing were assumed to have an elliptical shape similar to the fracture geometry formed from uniform pressure distributed fracture and the curving of subsequent fractures is attributed to opening and sliding of previously created fractures. Some studies (Rafiee et al., 2012) have utilized stress analysis to suggest a modification to the zipper fracturing to improve the SRV

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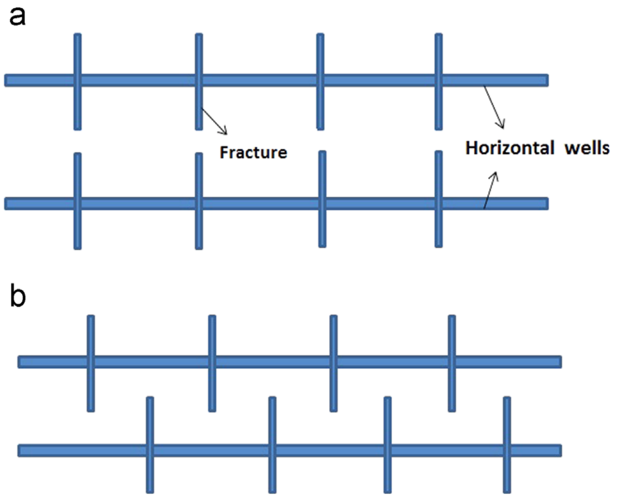

**Fig. 1.** (a) Conventional zipper fracturing. (b) Modified zipper fracturing.

based on heuristic arguments of complexity. However, a more rigorous modeling is needed to better understand the problem and to help improve design.

In this paper a fully coupled DD-based fracturing model is presented. The model can consider different boundary conditions to simulate the effect of previously created fractures as pressurized (during the flow back is restricted) and propped (proppant filled fracture). These boundary conditions allow the previously created fractures to open/close and shear as the next fracture propagates. The simulation examples include the conventional zipper fracturing technique (Fig. 1a) and a modified zipper fracturing technique (Rafiee et al., 2012) (Fig. 1b) performed on two parallel horizontal wells simultaneously and sequentially. In simultaneous zipper fracturing wells are fractured at same time and fractures are allowed to propagate simultaneously until they reach desired lengths. Then, a new set of fractures is created while the previously created fractures are kept pressurized or propped. This procedure is repeated from toe to heel along the horizontal lateral. In sequential zipper fracturing each lateral well is fractured individually. The operational benefits of both these methods were outlined in (Rodrigues et al., 2007).

In this paper, we numerically analyze the effect of both these techniques on the resulting stimulated reservoir volume providing a rational basis for optimizing the zipper fracturing. We also include the simulation of simultaneous propagation of multiple fractures in a single horizontal well. The fracture curving observed in such simulations is explained using the stress distribution plots around the fractures. The model can be used to study the effect of parameters such as in-situ stress, Young's modulus, Poisson's ratio, viscosity of the fluid on fracture propagation. The model calculates the fracture widths and pressures within each fracture as they propagate in response to injection to the wellbore.

## 2. Model development

The model developed in this work is based on 2D plane strain and uses the displacement discontinuity (DD) method (Crouch and Starfield, 1983) to calculate fracture deformation and propagation. The fluid flow inside the fracture network is governed by Lubrication equation Batchelor, 1967. The hydraulic fracture model couples fluid flow and fracture deformation through an iterative scheme between fracture aperture along the fracture length and fluid pressure. This is a non-linear problem that is solved using the Newton–Raphson method. The fracture propagation scheme for hydraulic fractures employs an iterative scheme to meet the propagation criterion. Joint DD element formulation is used to calculate the impact of stress shadow by specifying the fracture properties in terms of stiffness, when simulating the propped fractures. Finally, the fracture propagation path is determined using the maximum tensile–stress criterion in (Stone and Babuska, 1998). Each of these model components are briefly described below.

### 2.1. Displacement discontinuity method

In this model the displacement discontinuity boundary element method is used to find fracture deformation. In implementing this method, a fracture is divided into $n$ equal length elements. For a set of normal and shear stress acting on each element, the resultant normal and shear stresses on each fracture element is found by using superposition (Crouch and Starfield, 1983):

$$\overset{i}{\sigma}_s = \sum_{j=1}^{N} (\overset{ij}{A}_{ss}\overset{j}{D}_s + \overset{ij}{A}_{sn}\overset{j}{D}_n)$$

$$\overset{i}{\sigma}_n = \sum_{j=1}^{N} (\overset{ij}{A}_{ns}\overset{j}{D}_s + \overset{ij}{A}_{nn}\overset{j}{D}_n) \text{ (for } i = 1, N) \tag{1}$$

$\overset{ij}{A}_{ss}, \overset{ij}{A}_{sn}, \overset{ij}{A}_{ns} and \overset{ij}{A}_{nn}$ are the influence coefficients, representing the stresses due to constant shear and normal DD elements. The above system of linear equations can be solved for displacement discontinuity of each fracture element.

Using constant displacement discontinuity elements at the crack tips can lead to inaccurate values of stress intensity factors, so that this model incorporates a crack tip element (Yan, 2004) in which the normal displacement discontinuity between the crack surfaces is given by $u_y(x) = D_y(x/a)^{1/2}$where a is half length of the crack tip element, $D_y$ is the displacement discontinuity at the center of the crack tip element and, $x$ is the distance measured along the element from the tip of the crack. The influence coefficients and formulation for the crack tip element used herein is given in (Yan, 2004).

### 2.2. Joint model

To simulate propped fractures a simple linear elastic joint model given in (Crouch and Starfield, 1983) is used in this paper. A joint could have a compressible filling (proppant) or asperities which can experience closure on the application of external stresses. Joint closure is the amount of compression of a joint element (proppant in this case) due to the normal stress acting on it. Fig. 2 shows the relation between the normal stress and joint

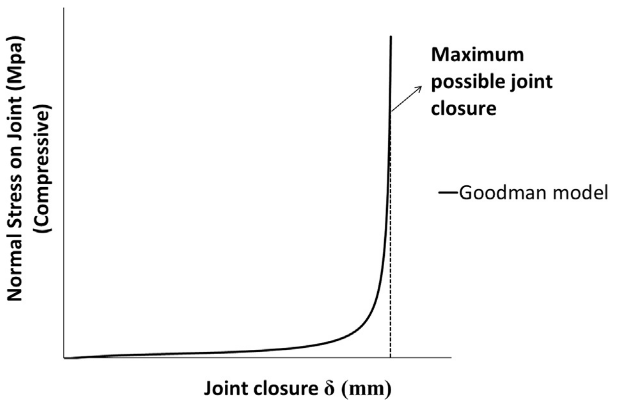

**Fig. 2.** The joint closure with respect to normal stress acting on it. The maximum joint closure will be less than the value of joint thickness.