Numerical Simulation of Non-Uniform Modified Zipper-Fracture Design

B. Sobhaniaragh [a,b,*], W.J. Mansur [a,b], F.C. Peters [a,b]

a. Modelling Methods in Engineering and Geophysics Laboratory (LAMEMO), COPPE, Federal University of Rio de Janeiro, RJ, Brazil.

b. Department of Civil Engineering, COPPE, Federal University of Rio de Janeiro, RJ, Brazil.

**. Corresponding author, Email address: behnamsobhani@yahoo.com, sobhaniaragh@coc.ufrj.br*

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Abstract

Thanks to astonishing advances in oil and gas technology, new fracturing designs have been developed to enhance production of trapped hydrocarbons, especially in low-permeable shale reservoirs. The new completion designs aim at mitigating side-effects of stress shadowing whereas enhance the far-field fracture complexity. This paper concentrates on the “Modified Zipper-Frac” (MZF) design as one of those techniques, which increases the stress interference between the fractures to enhance the hydrocarbon production. In the present 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 non-planar hydraulic fracture propagation for studying the stress shadow effects resulted from existing induced fractures. As opposed to original MZF, the stress shadow effects are managed through non-uniform fracture spacing. In this paper, 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, and in-plane shear stress have been studied.

Introduction

Multi-stage hydraulic fracturing in horizontal wellbores has led to a boom in the advancement of the unconventional reservoirs in particular shale gas and tight oil around the globe [1]. Multistage fracturing is a stimulation technique used to exploit low-permeability reservoirs by inducing complex hydraulic fracture network with high time efficiency. According to field analysis [2], it has been apparent that hydraulic fracture-surface area is substantially larger than that of assessed in conventional fracturing design. Such observation can be resulted from two factors. One refers to the fact that vast majority of tight sand and shale reservoirs are naturally fractured, such as Barnett shale [3]. Notwithstanding the presence of natural fractures, the other factor may be referred to the un-propped fractures, which can be induced as a result of stress shadowing effect during the inducing the main propped fracture. The un-propped fractures include micro-fractures emanating from the slippage along planes of weakness such as bedding planes, and the slippage of pre-existing natural faults or fissures [4]. Accordingly, the complex network of un-propped fractures appear to be the underlying reason explaining why some reservoirs demonstrate greater fracture complexity. Olsen et al. [5] investigated 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 decrease in the stress anisotropy is capable of activating the Mode I opening of planes of weaknesses, thereby generating complex fracture network which links hydraulically induced fractures to pre-existing natural fractures. Hence, presence of substantial fracture surface area leads to higher drainage of the low permeability reservoir and maximizing the Stimulated Reservoirs Volume (SRV).

One of the underlying factors in multi-stage hydraulic fracturing design is “stress shadow” or “altered-stress”, which is considered as stresses interference among multiple fractures placed closely on a single or multi-wellbores [6]. 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 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, based on the results obtained by Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS), Sookprasong et al. [7] concluded that the dominant perforation clusters are often recognized during simultaneously hydraulic fracturing. Furthermore, Spain et al. [8] elaborated that in unconventional reservoirs, around 40 to 60 percent of perforation clusters are without production. Indeed, by decreasing the fracture spacing, the stress shadowing effect increases dramatically and, as a result, the growth of some fractures suppresses the propagating of the others. Effect of stress shadowing on the various completion procedure on multi-lateral wellbores in the upper Barnett shale have performed by Vermylen and Zoback [9] using microseismic events. The results revealed that considerable discrepancies between different completion designs resulted owing to stress shadow effects.

In recent years, thanks to astonishing advances in the engineering and technology, various sophisticated designs have been developed to generate the complex fracture network, such as "Texas two-step" for an individual wellbore, "Zipper-Frac" and "Modified Zipper-Frac" (MZF) for multi-lateral wellbores [10]. Using a finite difference and explicit numerical scheme, Roussel and Sharma [11] and Manchanda and Sharma [12] showed that the lower fracture spacing can be achieved in the scenario of "Texas two-step" compared with conventional simultaneously fracturing. Furthermore, they purported that a stress reversal region with stress re-orientation of 90 degrees takes place in the adjacent to the main induced fracture. This zone imposes a confining condition on the fracture spacing which should be large enough to avoid the initiation of longitudinal fractures. Nevertheless, this hypothesis seems questionable because propagating of new fracture into the altered-stress region caused by the previous fracture can considerably change the local stresses. In addition, the numerical technique used in Refs. [11,12] and other available literature [13-16], is not capable of modelling of non-planar fracture propagation. In reality, owing to stress shadowing effect of pre-existing and/or simultaneous fractures, a non-planar hydraulic fracture may occur, as observed in experimental observations [17]. Inspired by the lack of robust and effective numerical tools in the available literature, in the present work, inspired by Phantom node method proposed by Hansbo and Hansbo [18] and cohesive segment method of Remmers et al. [19], the cohesive segments method in combination with phantom nodes, named as Cohesive Phantom Node Method (CPNM) [20,21], is used to model the non-planar hydraylic fracture problem in a quasi-brittle shale medium. As demonstrated by Song et al. [22], the formulation of Hansbo and Hansbo is equivalent to the original eXtended Finite Element Method (XFEM) [23], however the method of Hansbo and Hansbo has remarkable advantages compared with the implementation of the other, which can be mentioned that the implementation of Hansbo and Hansbo into commercial software packages, such as Abaqus, is much easier than that of original XFEM [24]. In the present paper, establishing the 2-D CPNM, effect and side-effect of stress shadowing in various completions design, in particular MZF, is studied. To this end, a parametric stuydy is carried out to investigate the effect of fracture spacing and the fracture length on the stress anisotropy, fracture propagation path, and the pore pressure of the shale formation.

Methodology

Simulation of the hydraulic fracturing in poro-elastic formation comprises the coupling of complex physical mechanisms including; deformation of the solid phase caused by the stress concentration owing to the fluid pressure on the fracture boundaries, fluid flow inside the porous medium enclosing the fracture, flow of the fracturing fluid through the crack, and infiltration of fracturing fluid into the poro-elastic formation, termed fluid leak-off.

The continuity equation for the fluid flow within the porous rock, which equates the raise rate of the fluid volume at a point to the rate of fluid volume flowing into the point during the time increment, is expressed as

$$\frac{d}{dt}\left(\int_V \rho_f \phi dV\right) + \int_S \rho_f \phi \boldsymbol{n}.\boldsymbol{v}_f dS = 0 \quad (1)$$

where $\boldsymbol{n}$ is the outward normal to fracture surface S, ρ_f is the mass density of the fluid, ϕ is the porosity of the medium, and $\boldsymbol{v}_f$ is the Darcy velocity of the pore fluid relative to the solid phase. For the sake of brevity, the equilibrium equation for the two-phase porous medium, the continuity and momentum equation for the fracturing fluid flow have not been expressed in this paper and the interested reader can refer to [20,21] for further details. Most studies on the modelling of hydraulic fracturing have assumed 1-D fluid loss pattern into the formation in a direction perpendicular to the fracture plane based on explicit Carter's fluid flow model. According to Carter's model, the fluid leak-off is expressed by an inverse square-root law of time of the form

$$v_L = \frac{c_L}{\sqrt{t}} \quad (2)$$

where v_L denotes leak-off velocity, c_L (in unit of $\mathrm{LT}^{-1/2}$) is the Carter's leak-off coefficient, t is the time elapsed since the beginning of the infiltration procedure. In addition, Carter proposed that the volume leaked fluid per unit area of the fracture, V_L, can be obtained as

$$V_L = 2c_L\sqrt{t} + S_p \quad (3)$$

where S_p is spurt-loss coefficient, which is the volume of the fluid that percolates instantaneously before forming a filter cake. The deficiency of the Carter model, which is independent of fluid pressure of the filter cake, motivates this research to employ another approach. In this paper, in order to treat the filter cake as a pressure-dependent layer, Settari's fluid leak-off model is employed by using a user-defined subroutine. By virtue of the proposed pressure-dependent model, the normal components of the fracturing fluid are defined as

$$v_{top} = c_{top}\left(p_F - p_{top}\right) \quad (4)$$

$$v_{bot} = c_{bot}\left(p_F - p_{bot}\right) \quad (5)$$

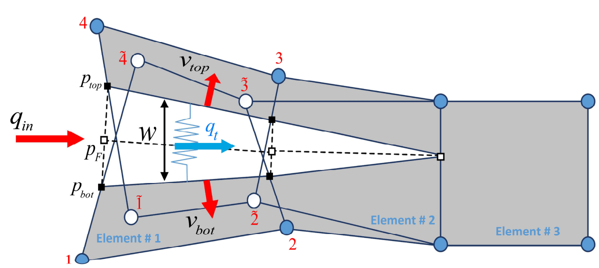

Fig. 1. Schematic plot of the fluid flow pattern model within the framework of CPNM.

where p_{top} and p_{bot} are the pore fluid pressures on the top and bottom faces of the crack, as depicted in Fig. 1, and c_{top} and c_{bot} are leak-off coefficients, which are pressure dependent and construed as the permeability of a filter cake built up on the walls of the fracture. In the present study, formulated by particular traction-separation laws, a Cohesive Crack Model (CCM) [26] is proposed which is independent of the constitutive characteristics of bulk material. By contrast with the Linear Elastic Fracture Mechanics (LEFM) in which the Fracture Process Zone (FPZ) is considered to lump into the crack tip, according to the CCM, the FPZ is aggregated into the crack surfaces. In addition, the CPNM is implemented into a commercial finite element analysis package (Aabaqus) along with user-defined subroutines in order to capture hydraulic fractures with erratic paths and FPZ ahead of the crack tip. It should be mentioned that mathematical framework presented in this paper is established based on that of [20,21] restricting the computational model to 2-D owing to computational expenses of the 3-D model. Consequently, the CPNM used in this study is the 2-D form of the one proposed [20]. Thus, the fracture initiation and propagation criteria and also description of the CPNM are not repeated herein due to conciseness purposes.

Computational Model

Fig. 2 represents 3-D configuration of the two horizontal wellbores. The trajectories of the horizontal wells are aligned with minimum horizontal stress, resulting in transverse fractures. As depicted in Fig. 2, the computational domain for hydraulic fracturing initiation and propagation simulation is a 2-D horizontal plane where the out-of-plane stress is vertical, which includes two horizontal wellbores, and perforation holes. The area "ABCD" which is the main domain of hydraulic crack propagation with fine meshes is of a length of 500 m and a width of 50 m. The size of the meshes out of the main domain is gradually decrease through the mesh transition. The whole domain is considered large enough to eliminate consequences of geometrical and pore pressure boundary conditions. The model is discretized into a fully saturated porous domain with CPE4RP elements (4-node bilinear displacement and pore pressure, reduced integration with hourglass control) together with enhanced hourglass control to remedy the problem of instabilities. The horizontal wellbores No. 1 and No. 2 are located in the plane of the horizontal stresses, $S_{h,\min}$ and $S_{H,\max}$, at the top and lower sides of the whole computational domain. In the proposed method, it is noted that the initial fractures or perforations are simulated by enriched elements, and the fracturing fluid flow is applied directly to edge phantom nodes of the enriched elements. The formation geologic parameters and the material properties are represented in Table 1 [20,21].

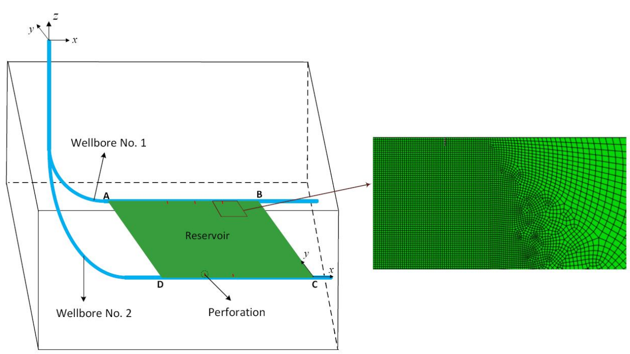

Fig. 2. 3-D configuration of the reservoir included two lateral wellbores and mesh generated around the perforation.

Table 1. Parameters for the hydraulic fracturing model.

Properties	Value
Elastic modulus of formation	1.294 MPa
Poissons ratio	0.25
Fluid viscosity	1 cp
Critical fracture energy	28 kN/m
Damage Initiation Stress of barrier layers	0.36 MPa
Damage Initiation Stress of pay zone	0.32 MPa
Formation effective permeability	4.9346165e-19 m^2
Specific weight of fluid	9.8 kN/m^3
Initial pore pressure	795 kPa
Pressure dependent leak-off coefficient	5.879e-10 $m^3/kPa.s$
Porosity	0.2
Injection rate per unit reservoir thickness	1.5e-3 m^3/s

Results and discussion

In this section, taking the MZF completion design into account, the impacts of stress shadowing affected by Fracture Spacing (FS) on the stress anisotropy, shear stress, and pore pressure of the formation are investigated in detail by conducting a number of simulation runs. As reported in [10,11], by closely FS, the stress shadow effects during fracture extension would lead to induced fracture complexity and, as a result, generating a more extensive fracture network. In this research, a critical value of FS is defined in such a way that the fracture propagates in a straight path (without deviation) under the stress shadowing and achieves the desired length.

Fig. 3 shows the pore pressure of the formation after terminating the third stage and fifth stage in MZF design in two lateral horizontal wellbores. By setting the FS to 71 m, the first fourth fractures do not deviate under the stress interference of previous fracture(s) and follow the straight path. It can be seen, the pore pressure of the formation exhibits symmetric distribution with respect to the fracture paths. As depicted in Fig. 3a, by using uniform FS, the Fr. #5 is deviated towards Fr. #4 owing to stress shadowing effect of pre-existing fractures, leading to asymmetric distribution of the pore pressure and increasing the risk of well communication. Inspired by the technique proposed in Refs. [14,26], the stress shadow effects are managed

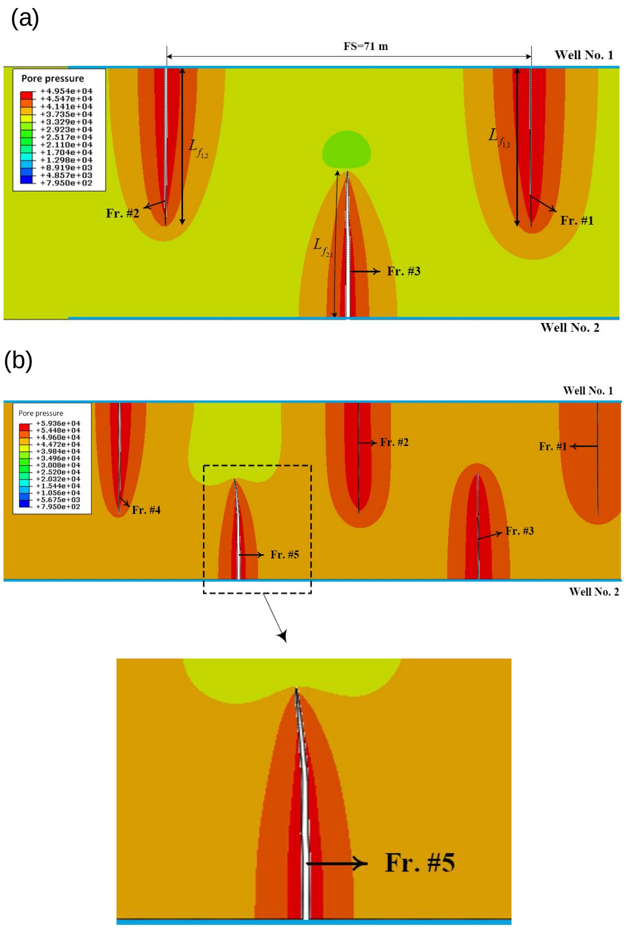

Fig. 3. Pore pressure contour of the formation for the case of MZF design with critical value of FS=71 m: **a)** after terminating the 3rd stage, **b)** after terminating the 5th stage.

through non-uniform fracture spacing. The critical value of the FS between Fr. #2 and Fr. #5 has been determined as 105 m so that the Fr. #5 propagates in a straight path, as demonstrated in Fig. 4. By comparing Figs. 3 and 4, one can see that the pore pressure of the formation declines as the FS increases.

Fig. 5 demonstrates the variation in shear stress in the direction perpendicular to the Fr. #1 for MZF design with uniform and non-uniform FS. As can be found in this figure, the behavior of the in-plane shear stress for both non-uniform and uniform FS, in the interval between Fr. #1 and Fr. #2 is analogous. However, by increasing the FS from 71 m (in uniform FS) to 105 m (non-uniform FS), the shear stress demonstrates different states. As the FS decreases, the smaller part of the formation experiences the alteration in both value and direction of shear stress owing to stress shadowing. In addition, the variation in shear stress for two different distances (12 m and 18 m) from the wellbore No. 1 has been depicted. It is interesting to note that the variation in shear stress near the fracture tip of the opposite fracture, which propagates from opposite wellbore, is significantly higher than that with further distance to fracture tip. Indeed, the alteration in shear stress leads to activate the plains of weaknesses and natural fractures which exist in the non-conventional reservoirs such as shale plays [27].

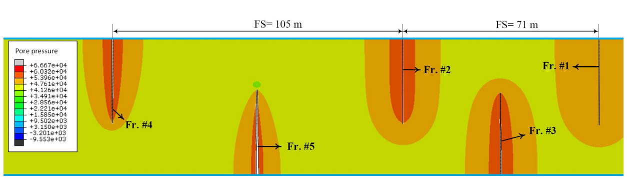

Fig. 4. Pore pressure contour of the formation for the MZF design with non-uniform FS.

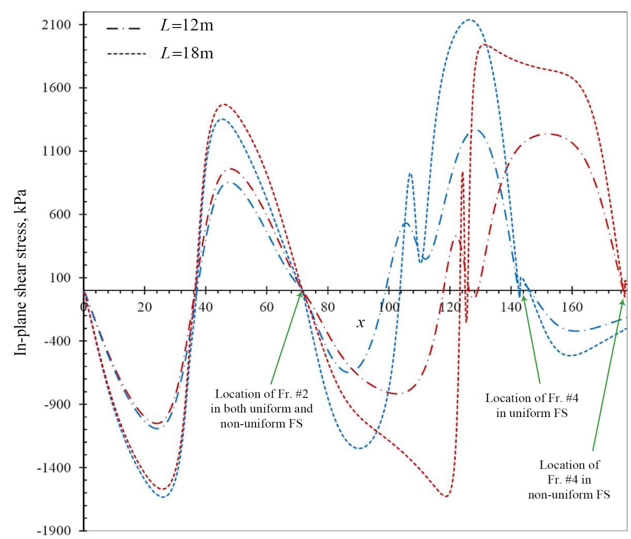

Fig. 5. Illustration of variation in shear stress in the direction perpendicular to the Fr. #1; Red line: MZF with non-uniform FS, Blue line: MZF with uniform FS.

Conclusions

This paper studied stress shadowing effects as a function of fracture spacing in MZF design in two lateral horizontal wellbores. Based on a fully coupled pore-pressure stress analysis, the CPNM has been used to simulate the initiation and propagation of non-planar cohesive fractures along the arbitrary, solution-dependent paths. By conducting a number of simulation runs, it has been inferred that the fifth fracture in MZF design is deviated from the straight path and moves towards the fourth fracture owing to stress shadow effects, leading to increase the risk of opposite wellbores communications. By increasing the fracture spacing between third and fourth fractures to the critical value, the stress interferences are mitigated and all fractures follow straight propagation paths. Furthermore, results obtained showed that propagation of the fracture from opposite wellbore has the capability to alter shear stress in the formation and, as a result, to activate the plains of weaknesses and natural fractures, which exist in the non-conventional reservoirs such as shale plays.

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