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Numerical modelling of fluid leak-off during hydraulic fracturing treatments in saturated porous media

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ABSTRACT: Hydraulic fracturing is a technique used to increase the productivity of oil and gas reservoirs by increasing the permeability of such a reservoir via injecting highly pressurized fluid. A key parameter controlling the efficiency of such a stimulation technique is to capture and minimize the amount of fluid leaked into the surrounding porous media. In the current study, a novel fully coupled XFEM numerical hydro-fracture model is introduced to capture the effect of fluid loss on the efficiency of the fracturing treatment through the generalized leak-off model. In the proposed generalized leak-off model, the effect of the pressure drop on the hydrofracture faces and the associated decrease in the amount of leaked fluid due to the rapid settlement of injecting fluid proppants is considered. The formation of the so-called cake layer has been shown to have a great impact on fracturing efficiency, particularly when dealing with medium permeability reservoirs. Overall, the developed framework showed to be highly capable of predicting the hydro-fracking process, especially in medium-range permeability formations.

KEYWORDS: Hydraulic fracturing, Fluid leak-off, XFEM; Medium permeability reservoirs.

1 INTRODUCTION.

Hydraulic fracturing is a versatile technique mainly used for the stimulation of oil and gas reservoirs for enhancing production and recovery. During the course of hydraulic fracturing treatments, a huge amount of pressurized fluid is deliberately injected into the rock formation so as to increase the overall permeability either by expanding pre-existing natural fracture networks or generating a new one. Inevitably, the efficiency of the fracturing job may be substantially reduced as a result of fluid leak-off into the surrounding porous media. Indeed the accurate prediction of leaked fracturing volume is crucial to the estimation of stimulated rock volume (SRV), the evaluation of pumping pressures and the assessment of the total amount of injected fluid [1].

Over the past few decades, extensive developments were carried out in the study of hydraulic fracturing treatments in a range of analytical developments e.g., [2, 3], numerical simulations [4], and experimental investigations [5]. The numerical models have proven to be the most rigorous and cost-effective tool to tackle the complex nature of hydraulic fracturing due to their great flexibility in adapting the discrepancies in geological formations. A major step forward in this regard has been due to mesh independent approaches such as X-FEM [6, 7], Meshless [8], and Phase-field [9] which offer superior computational performance. Despite the capability of the current state-of-art frameworks in incorporating fluid exchange between the hydro-fracture and the surrounding domain, they generally suggest unrealistic leak-off rates that overestimate the fracturing fluid loss. A common shortcoming is that the pressure field is assumed to be continuous across the fracture which critically violates the physics of the problem in reality. In fact, the so-called cake layer formed along the hydro-fracture faces introduces a discontinuity in the fracturing fluid pressure with respect to the pore fluid.

Leak-off of fracturing fluid into the formation is typically incorporated by applying Carter's relation which is derived on the basis of the assumption of 1-D infiltration of a viscous fluid through a rigid porous block [10]. Based on [11], three distinct zones can be recognized in the host matter in relation to leak-off: a filter cake formed due to trapped solid additives in the fracturing fluid along the fracture face; a filtrate zone affected by the invasion of the fracturing fluid; and far reservoir zone over which the permeability and pore fluid is not affected due to the fracturing process.

In this study, a novel X-FEM enrichment strategy is proposed which elaborate the independent pressure field within the hydro-fracture with respect to the bulk. To this end, both the pressure and displacement fields are considered to be discontinuous and enriched by the Heaviside enrichment function, while an additional set of enriched degrees of freedom are included in the fluid pressure discretization to account for the independent fracturing pressure.

2 HYDRAULIC FRACTURING FORMULATION.

Assuming a solid-fluid mixture of volume \mathbf{W} (Figure 1), the momentum balance equation satisfying the condition of equilibrium for quasi-static conditions can be written as

$$\nabla \cdot \sigma + \rho \mathbf{b} = 0 \quad (1)$$

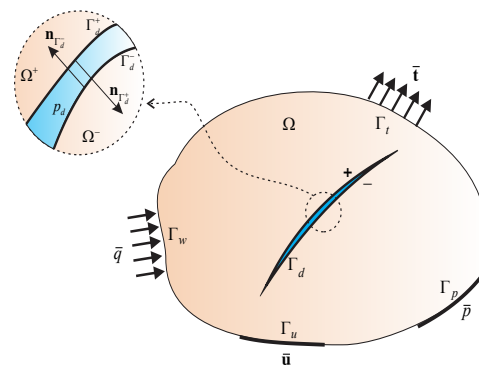


Figure 1. Boundary conditions of a fractured porous media.

where ρ is the average density of the whole mixture, \mathbf{b} is the body force vector, σ is the total external stress. The elastic stress-strain relation is $\sigma' = \mathbf{D}\epsilon$ where the effective stress for the porous medium is $\sigma = \sigma' - \alpha p \mathbf{I}$; σ' and \mathbf{D} are the effective stress and elastic stiffness matrix in drained condition. $\alpha = 1 - (K_T / K_S)$ is Biot's coefficient; K_S and K_T are the bulk moduli of solid grains and porous medium, respectively. The natural and essential boundary conditions on the exterior of the solid skeleton are $u = \bar{u}$ on Γ_u , $\sigma \cdot n_T = \bar{t}$ on Γ_t . The nonlinear behaviour of fractured media in the cohesive zone is modelled by using a traction-separation law $\mathbf{t} = \mathbf{t}(h)$ where \mathbf{t} is the cohesive traction and h is the crack opening.

The combination of linear momentum balance (referred to as Darcy's fluid flow) within porous media and the continuity equation results in the u-p formulation of porous media [12].

$$\nabla \cdot [k_f (-\nabla p + \rho_f \mathbf{b})] + \alpha \nabla \cdot \dot{\mathbf{u}} + \frac{1}{Q} \dot{p} = 0 \quad (2)$$

where k_f is the matrix permeability with respect to pore fluid, ρ_f is the fluid density, $1/Q = n/K_f + (\alpha - n)/K_s$ in which K_f is the fluid compressibility and natural and essential boundary conditions of the fluid phase are considered as $p = \bar{p}$ on Γ_p , $w \cdot n_r = \bar{q}$ on Γ_q (Figure 1). For the fluid within the fracture, the fracture permeability in the case of a Newtonian fluid is estimated based on the cubic law [13].

According to the generalized leak-off model [11], the fluid flow through the cake layer is presented in term of the pressure drop Δp_w (Figure 2) and cake resistance factor referred to as transmissibility factor T_w in which the fluid leak-off is as follow

$$\dot{w} \cdot n = T_w \cdot \Delta p_w \quad (3)$$

where T_w is calculated using T_w^0 (transmissibility in the test) which is in turn found experimentally via filtration tests with thin wafers [1]. n is the normal unit vector of the fracture, $\Delta p_w = p_f - p_w$ is the pressure drop across the filter cake zone and \dot{w} is the velocity through the zone.

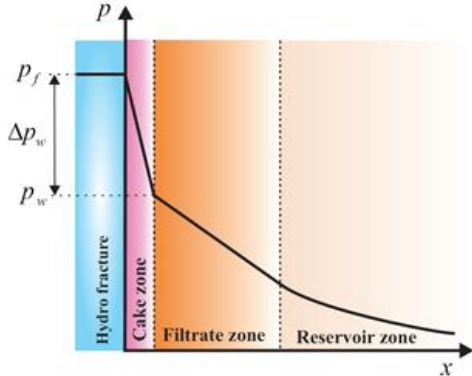


Figure 2. Schematic representation of different regions and the corresponding pressure drops in the host rock.

The filter cake transmissibility (Figure 3) was shown to have a relationship with Carter's leak-off coefficient C_w as follow [11]

$$T_w(t) = \frac{C_w}{\sqrt{t - t(x)} \cdot \Delta p_w} \quad (2)$$

and the total leak-off for the fracturing fluid is as follow

$$\begin{aligned} \dot{w}_{\Gamma_d}^+ \cdot n_{\Gamma_d}^+ &= T_w \Delta p = -T_w (p_f - p^+) \quad \text{on } \Omega^+ \\ \dot{w}_{\Gamma_d}^- \cdot n_{\Gamma_d}^- &= T_w \Delta p = -T_w (p_f - p^-) \quad \text{on } \Omega^- \end{aligned} \quad (3)$$

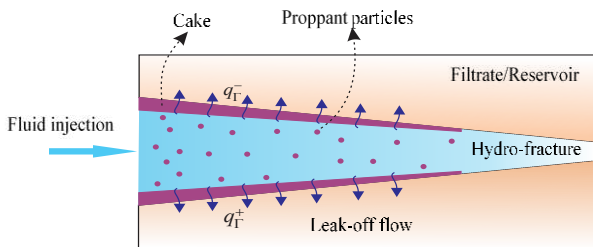


Figure 3. Schematic representation of hydro-fracture geometry and fluid loss.

To obtain the coupling fluid exchange of the flow continuity equations, the weak form is derived by multiplying the strong form with an arbitrary test function and integrating over the domain by incorporating X-FEM discontinuous Heaviside function for both solid and fluid phases in addition to the independent fracture degrees of freedom for the fluid inside the

cavity (Figure 4).

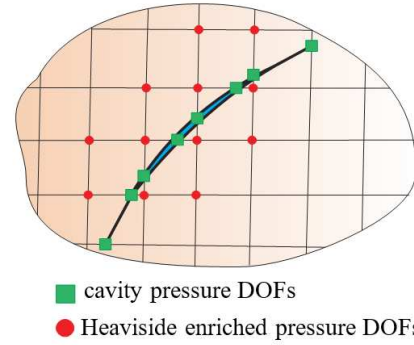


Figure 4. XFEM discretization and enriched DOFs of the pressure field.

3 NUMERICAL SIMULATIONS

A semi-circular domain with a diameter of 80m (representing an infinite porous medium) is selected according to the available analytical solutions [2, 3]. The formation comprises an initial fracture with a negligible length of 0.2m and propagates in pure mode I, though the model can be further extended to account for mixed-mode crack propagation, multiple fracture treatment and crack branching. The solid block includes an elastic modulus $E=15.9\text{GPa}$, $k=1e-12\text{m}^2$, $\nu=0.33$ and a solid grain specific density of 2. All analyses are performed under plane strain conditions using 2420 4-node quadrilateral containing 2448 nodal points for both solid and fluid phases, and a 2-node truss element for the additional fracture.

A fracturing fluid $\mu=1e-3\text{Pa}\cdot\text{s}$ with the constant rate $q_{in}=1e-4\text{m}^2/\text{s}$ is injected into the borehole initiating the fracturing process. The crack length increments are set to be 0.05m, while the simulation is performed for 10s with the time increments of $\Delta t=0.01\text{s}$.

Figure 5 depicts the hydro-fracture evolution of the reservoir under various interface permeabilities. According to this figure, the proposed method, unlike the continuous pressure method, can predict the fracture evolution even for high transmissibility factors (i.e. $T_w=0.1\text{m}^2/\text{s}/\text{kg}$). In this context, obviously, the crack length and the crack opening increase with the decrease of the transmissibility factor. Another important feature is that for high transmissibility factors (i.e. $T_w=0.1\text{m}^2/\text{s}/\text{kg}$ and $T_w=0.05\text{m}^2/\text{s}/\text{kg}$) the fracturing process is considerably sensitive to the change of the T_w during the fracture evolution. Accordingly, fracture growth stops a few seconds after the treatment, while it continues to grow when the effect of the time factor is taken into account. This phenomenon is clearly illustrated in Figure 6. In this figure, the effect of the time factor on T_w is depicted for various interface permeability at the end of the analysis (i.e. $t=10\text{s}$). This figure shows that as the fracturing proceeds, the accumulative trapping of the fracturing fluid proppants reduces on the zones closer to the fracture tip. Thus, the transmissibility factor at the end of the analysis is identical for all T_w cases at the injection point, while it changes significantly when reaching the crack front. Based on this justification, it can be clearly inferred that the crack length and opening for such transmissibility factors are enhanced when the effect of the incremental formation of the cake layer during the fracturing is taken into account. As the interface permeability decreases, the effect of the cake formation on the fracture progress decreases to the extent that for $T_w=1e-4, 1e-3\text{m}^2/\text{kg}$, hydraulic fracturing evolves irrespective of the incremental cake layer formed by the proppant particles.

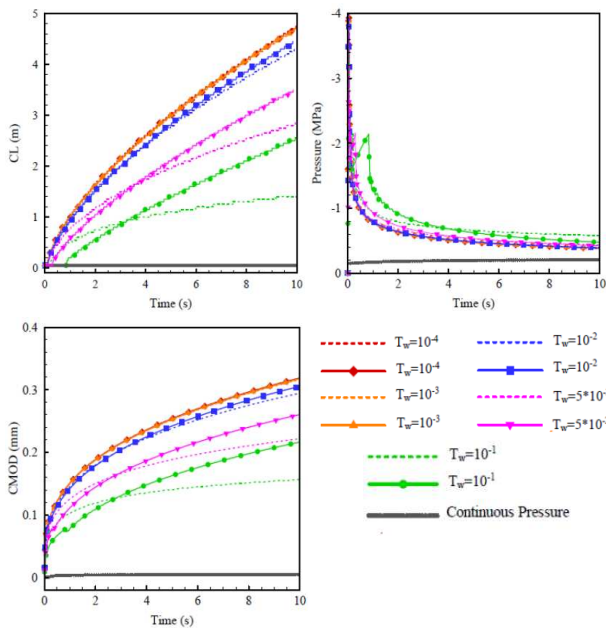


Figure 5. Crack length (CL), crack mouth opening displacement (CMOD) and crack mouth pressure of the hydrofracture (continuous line for constant T_w and dashed line for time dependent T_w).

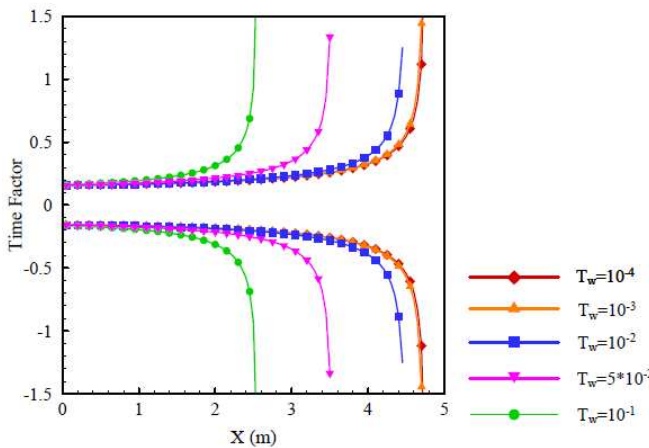


Figure 6. variation of time factor along the fracture at the end of hydrofracture analysis ($t=10s$).

4 CONCLUSIONS

In this paper, the effect of fluid loss on hydraulic fracturing efficiency was studied through a novel fully coupled X-FEM multiphase porous media in which fracture-independent degrees of freedom were incorporated. The effect of the proppant trapping was considered via a generalized leak-off model in which the pressure drop across the hydrofracture was taken as the primary source of fluid leakage for both constant and time-dependent interfacial transmissibilities. The developed numerical framework not only was capable of predicting the fracture evolution of low permeability reservoirs but also, unlike the existing fully coupled methods, it could comprehensively predict the hydrofracture propagation in highly permeable reservoirs.

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