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Multi-phase fracturing fluid leakoff model for fractured reservoir using extended finite element method

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A B S T R A C T

Fracturing fluid leakoff into natural fractures determines the propagation of a hydraulically-driven fracture, especially for slick-water fracturing in unconventional reservoirs. This paper proposes a multi-phase model of fluid flow in a fractured porous medium using the extended finite element method (XFEM), and investigates the effects of pre-existing natural fissures on fracturing fluid leakoff. This model introduces an absolute value of signed distance function and appropriate branch functions to refine the local discontinuities in the modeled pressure derivatives across the fractures. This local refinement is independent of the matching grid and is easily incorporated into XFEM-based stress analysis for crack propagation modeling. A numerical example is provided, in which the cumulative leakoff volume versus exposure time behavior for a single natural fracture with different intersection angles with a hydraulic fracture is investigated, along with that of a single non-intersected natural fracture at different distances from a hydraulic fracture. In addition, the leakoff behavior into a pre-existing fracture is compared with that into matrix rock. These comparisons indicate that the cumulative leakoff volume is linearly proportional to the square root of the leakoff time for matrix rock unaffected by fractures, while it is linearly proportional to the leakoff time in the case of non-intersected fractures.

1. Introduction

In hydraulic fracturing, the leaking of fracturing fluid from the main hydraulic fracture limits the efficiency of the fracturing process (Economides et al., 2007; Peirce, 2015). Modeling such fluid leakage is therefore important for both prefrac design and postfrac evaluation. Classical leakoff theory assumes that fluid leakoff is governed by three mechanisms, which describe the leakoff-fluid viscosity and compressibility effect in the invasion zone (C_v), the reservoir-fluid viscosity and compressibility effect (C_c), and the wall-building effect (C_w). In addition, it has been shown that the leakoff velocity is inversely proportional to the square root of the exposure time (Penny et al., 1985). A comprehensive model has been developed to investigate the effects of variations in pressure, rheological behavior, filter-cake erosion, and boundary conditions on the fluid leakoff (Yi and Peden, 1994). However, some laboratory tests have demonstrated that the presence of mobile oil causes differences in fluid leakoff behavior compared to that observed for totally water-saturated cores in conventional reservoirs (Gadiyar and Gupta, 1998).

Pre-existing natural fractures are commonly found in unconventional reservoirs, such as tight gas, shale, and coalbed methane deposits (Mayerhofer et al., 2010). In a naturally fractured reservoir, fluid leakoff primarily occurs at the points where the hydraulic fracture and the pre-existing fissures in the rock intersect. To investigate this behavior, a commercial finite element analysis program has been used to establish the perturbations around intersection points to flow for power law type fracturing fluid. But no more details are presented on fluid leakoff behavior for fissured reservoirs (Stahl and Clark, 1991). In addition, Li et al. (2007) have derived an analytical solution to describe fluid leakoff behavior for naturally fractured gas reservoirs, neglecting both the compressibility of the formation fluid and the pressure drop across the filter

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cake. Guo and Liu (2014a; 2014b) have examined fluid leakoff while considering the aperture and fractal features of natural fractures, along with other factors such as filter cake consisting of polymer residues, formation fines and additives, matrix filtration, stress sensitivity, and temperature. Finally, Zhao et al. (2014a) have established a numerical model to simulate the influence of natural fractures on fluid leakoff by treating the naturally fractured rock as equivalent continuum media. These fluid leakoff models assume single-phase flow or piston-like displacement. Moreover, they are rebellious for fluid leaking from hydraulic fracture network, and are hard to be coupled with fracture propagation model.

At present, massive (or high-volume) hydraulic fracturing is vitally important for the development of unconventional reservoirs, as it can be used to form the largest possible stimulated reservoir volumes (SRVs) (Wu et al., 2012; Fisher et al., 2005). To simulate the complex fracture network propagation required for such large-scale fracturing, the extended finite element method (XFEM) has been widely used (Daux et al., 2000; Dahi-Taleghani, 2009; Dahi-Taleghani and Olson, 2011; Keshavarzi and Jahanbakhshi, 2013; Gordeliy and Peirce, 2013; Mohammadnejad and Khoei, 2013a; Chen, 2012; Lamb, 2011; Lamb et al., 2013; Zhao et al., 2014b; Meschke and Leonhart, 2015). However, perfect coupling does not exist between fracturing fluid flow behavior in hydraulically induced fractures, pre-existing fractures, and matrix rock. In this work, to simulate fluid leakoff in naturally fractured reservoirs, we extend our previously developed single-phase fluid flow model (Liu et al., 2015) to a multi-phase fluid flow model using XFEM, which can couple with stress analysis and fracture propagation to simulate complex fracture network propagation for high-volume fracturing.

2. Governing equations

To model hydraulic fracturing in this study, we assume that there is no interphase mass transfer and ignore the temperature change caused by the injection of the fracturing fluid. Then, the wetting phase (fracturing fluid) is the only source/sink term. The strong and associated weak forms of the governing equations for fluid flow within both the matrix and fracture domains are presented in this section.

2.1. Strong form

According to the law of mass conservation, the continuity equations for wetting and non-wetting phase flow in the matrix domain are expressed as

$$\left(\frac{\alpha_m-\phi_m}{K_s}S_{w,m}\left(S_{w,m}+\frac{p_{c,m}}{\phi_m}C_{s,m}\right)+\frac{\phi_m S_{w,m}}{K_w}-C_{s,m}\right)\frac{\partial p_{w,m}}{\partial t}$$
$$+\left(\frac{\alpha_m-\phi_m}{K_s}S_{w,m}\left(S_{nw,m}-\frac{p_{c,m}}{\phi_m}C_{s,m}\right)+C_{s,m}\right)\frac{\partial p_{nw,m}}{\partial t},$$
$$+\nabla\cdot\left(-\frac{\mathbf{k}_m k_{rw,m}}{\mu_w}\nabla p_{w,m}\right)+Q_{stc,w}B_w=0 \tag{1}$$

$$\left(\frac{\alpha_m-\phi_m}{K_s}S_{nw,m}\left(S_{w,m}+\frac{p_{c,m}}{\phi_m}C_{s,m}\right)+C_{s,m}\right)\frac{\partial p_{w,m}}{\partial t}$$
$$+\left(\frac{\alpha_m-\phi_m}{K_s}S_{nw,m}\left(S_{nw,m}-\frac{p_{c,m}}{\phi_m}C_{s,m}\right)\right.$$
$$\left.+\frac{\phi_m S_{nw,m}}{K_{nw}}-C_{s,m}\right)\frac{\partial p_{nw,m}}{\partial t}+\nabla\cdot\left(-\frac{\mathbf{k}_m k_{rnw,m}}{\mu_{nw}}\nabla p_{nw,m}\right)=0. \tag{2}$$

Similarly, the continuity equations for wetting and non-wetting phase fluid flow inside the fracture domain are expressed as

$$\left(\frac{S_{w,f}}{K_w}-C_{s,f}\right)\frac{\partial p_{w,f}}{\partial t}+C_{s,f}\frac{\partial p_{nw,f}}{\partial t}+\nabla\cdot\left(-\frac{k_f k_{rw,f}}{\mu_w}\nabla p_{w,f}\right)=0, \tag{3}$$

$$C_{s,f}\frac{\partial p_{w,f}}{\partial t}+\left(\frac{S_{nw,f}}{K_{nw}}-C_f^s\right)\frac{\partial p_{nw,f}}{\partial t}+\nabla\cdot\left(-\frac{k_f k_{rnw,f}}{\mu_{nw}}\nabla p_{nw,f}\right)=0, \tag{4}$$

where α is Biot's constant, ϕ is the porosity, K is the bulk modulus, p is the pore fluid pressure, p_c is the capillary pressure, S is the saturation, $\mathbf{k}$ is the matrix permeability tensor, k is the permeability, k_r is the relative permeability, μ is the pore fluid viscosity, Q_{stc} is the surface source/sink term, B is the formation volume factor, and t is time. The subscripts s, w, and nw indicate the solid, wetting, and non-wetting phases, respectively, while m and f indicate the rock matrix and fracture, respectively. The parameters $C_{s,m}$ and $C_{s,f}$ are defined as

$$C_{s,m}=\phi_m\frac{\partial S_{w,m}}{\partial p_{c,m}}, \tag{5}$$

$$C_{s,f}=\frac{\partial S_{w,f}}{\partial p_{c,f}}, \tag{6}$$

and the fracture permeability is calculated according to the formula (Witherspoon et al., 1980)

$$k_f=\frac{1}{f}\frac{b^2}{12}, \tag{7}$$

where f is a morphological parameter accounting for the difference between the real and the ideal parallel fracture, ranging from 1.04 to 1.65, and b is the fracture width in meters.

2.2. Weak form

In order to deduce the weak form of the governing equations, a two-dimensional domain Ω bounded by Γ is considered, as shown in Fig. 1. A natural fracture with high k_f inside Ω is treated as a one-dimensional discontinuous line, because b is much less than the fracture length. Γ_f^+ and Γ_f^- are used to represent the two faces of the fracture.

The pressure distributions for wetting and non-wetting phase are preset by the initial conditions, while the initial saturations can be calculated using capillary pressure curve.

$$p_{l,m}(\mathbf{x},0)=p_{l,m}^0,\quad \forall\mathbf{x}\in\Omega;\, l=w,nw. \tag{8}$$

The essential boundary conditions are imposed on the external