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E.V. Dontsov, A.P. Peirce

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A multiscale Implicit Level Set Algorithm (ILSA) to model hydraulic fracture propagation incorporating combined viscous, toughness, and leak-off asymptotics

E.V. DONTSOV[1] and A.P. PEIRCE[2]

[1] *Department of Civil and Environmental Engineering, University of Houston, Houston, Texas, 77204, USA.*
[2] *Department of Mathematics, University of British Columbia, Vancouver, British Columbia, V6T 1Z2, Canada.*

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This study uses an Implicit Level Set Algorithm (ILSA) to model the propagation of planar hydraulic fractures in situations when their progress is determined by an interplay of fluid viscosity, rock fracture toughness, and fluid leak-off into the formation. One of the key features of our approach is the use of the three-process tip asymptotic solution both as a propagation condition and to capture the multiscale behavior in a weak sense. Using this special tip asymptote is necessary because the validity region of the classical square root fracture opening solution (stemming from linear elastic fracture mechanics) is often limited to a small zone near the fracture tip, which can only be captured by a very fine mesh. In addition, this validity zone depends on the velocity of fracture propagation, so that slow and fast portions of the fracture front may experience different near-tip behavior. The multiscale tip asymptotic solution, on the other hand, has an increased validity region, which makes it possible to capture the near-tip multiscale behavior on a coarse mesh and yields a computationally efficient algorithm. The presence of leak-off also complicates the model considerably as it involves a delay term containing the trigger time history, which depends on the earlier fracture front positions. Moreover, the leak-off from tip elements in which the fracture front speed changes significantly requires special treatment. This three-process asymptotic solution is used to solve the fully coupled integro-delay-PDE model for a propagating planar hydraulic fracture by using a level set algorithm in conjunction with the tip asymptotic solution to locate the moving fracture front and to capture mulitscale behavior. Firstly, the developed algorithm is validated against a reference solution for an axisymmetric hydraulic fracture. Secondly, a set of numerical examples involving three stress layers is presented to illustrate the variation of the multiscale near-tip behavior along the fracture perimeter and the need to use the multiscale asymptotic solution in a hydraulic fracturing simulator.

Key words: Hydraulic Fracture, Level Set Methods, Multi-Scale Phenomena, Stress Jumps, Leak-off.

1 Introduction

Hydraulic fractures (HF) are cracks that are produced by the injection of a viscous fluid into a solid medium. HF occur in nature as kilometers-long vertical dikes that bring magma from deep underground chambers through the rock to the earth's surface driven by buoyancy [1, 2, 3, 4, 5, 6, 7], or as fluid-filled cracks in glaciers [8]. The most common industrial application of HF is in the stimulation of oil and gas reservoirs to enhance the recovery of hydrocarbons by the creation of permeable pathways, see e.g. [9]. In addition, HF are used for accelerating the waste remediation process [10], waste disposal [11], and preconditioning in rock mining [12].

Apart from buoyancy-driven HF studies most HF models cater for petroleum applications. One of the first models developed was the Khristianovich-Zheltov-Geertsma-De Klerk (KGD) model [13], in which a line fracture propagates under plane strain elastic conditions. Another early model is the Perkins-Kern-Nordgren (PKN) model [14, 15], in which a vertical planar fracture with fixed height propagates horizontally. Later, the pseudo-3D (P3D) model was developed [16] as an extension of the PKN model that allows for height growth. There are several variations

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