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Modeling of hydraulic fracturing in ultra-low permeability formations: The role of pore fluid cavitation

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A B S T R A C T

Hydraulic Fracturing (HF) refers to the process of nucleation and growth of tensile fractures in a reservoir formation by means of flow-induced pressurization. The processes in the fracture process zone (FPZ) of a fluid-driven fracture involve a non-linear coupling between fracturing-fluid flow, rock deformation and diffusion of pore fluid. Identifying all the key physical processes is critical for reliably modeling and simulating fluid-driven fractures. The role of cavitation and subsequent alteration in pore fluid saturation is often ignored in hydraulic fracturing simulations, i.e., the pore fluid is modeled to be able to sustain arbitrarily large negative pressures without undergoing cavitation. Using multi-physics Finite Element Analyses (FEA), we show that ignoring cavitation may lead to spurious outcomes in FEA simulations of fluid-driven fractures in ultra-low permeability formations. The FEA simulations, in the absence of cavitation, predict an unrealistically large suction (negative pressure) ahead of the crack tip, which grows without bound upon refinement of the FEA mesh. Owing to such a large suction at the crack tip, the breakdown pressure obtained from the FEA simulations is anomalously large and lacks objectivity (i.e., progressively increases upon a continued refinement of the FEA mesh). Mechanistic insights gained from FEA simulations suggest that the negative pressure ahead of the crack tip is likely to cause cavitation of the pore fluid, resulting in creation of a partially-saturated region around the crack tip. This means that irrespective of the initial saturation of the rock, inclusion of cavitation and subsequent alteration in pore fluid saturation in FEA simulations is necessary for objectively modeling the fluid-driven fractures in ultra-low permeability formations. The revised FEA simulations of hydraulic fracturing show that the inclusion of cavitation and subsequent alteration in pore fluid saturation in FEA simulations eliminates the unrealistically large suction at the crack tip, regularizes the breakdown pressure, and removes the noted lack of objectivity.

1. Introduction

Hydraulic fracturing involves opening and propagation of tensile fractures inside rock formations by means of a flow-induced pressurization [1,2]. Hydraulic fracturing is primarily used in the oil/gas industry as a means of stimulating unconventional reservoir formations, such as shales and tight sands. Unconventional reservoirs are ultra-low permeability formations and constitute a significant source of hydrocarbons worldwide. However, because of their ultra-low permeability, the

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Nomenclature

$\boldsymbol{\sigma}$	total stress tensor (psi)
$\boldsymbol{\sigma}'$	effective stress tensor (psi)
P_p	total pore pressure (psi)
$\mathbf{q}$	fracturing fluid flux (in.^{2}/s)
Q_0	injection rate (in.^{2}/s)
k_a	absolute permeability of the rock (in.^{2})
μ	viscosity (dynamic) of the pore fluid (cP)
ρ	density of the pore fluid (lbs/in^3)
g	acceleration due to gravity (in./s^2)
k_{Fluid}	hydraulic conductivity (in./s)
μ_f	viscosity (dynamic) of the fracturing fluid (cP)
M	biot modulus (psi)
α	biot coefficient ()
$T_{\max}$	cohesive strength of the rock (psi)
G_c	fracture energy (psi-in)
K_{Ic}	fracture toughness (psi-$\sqrt{\text{in.}}$)
K'	$4\sqrt{\frac{2}{\pi}}K_{Ic}$ (psi)
$\lambda,\ G$	Lamè constants (psi)
$E,\ \nu$	Young's modulus (psi) and Poisson ratio, respectively
E'	plane strain modulus ($= E/(1-\nu^2)$) (psi)
Δ	fracture opening (in)
$l_a,\ w_a$	length and width of the fracture, respectively (in)
P_{BD}	breakdown pressure (psi)
S	saturation of the matrix ()
S_{irr}	irreducible saturation ()
$\mathscr{E}$	volumetric strain ()
$\mathbf{I}$	identity matrix ()
P_c	capillary pressure ($= P_{\text{Vap}} - P_{\text{Liq}}$) (psi)
$P_{\text{Liq}},\ P_{\text{Vap}}$	partial pressures of the liquid and vapor phase, respectively (psi)
Δ_i	fracture opening at the onset of damage (in)
Δ_f	fracture opening at complete damage (in)
$\chi_{\text{Liq}},\ \chi_{\text{Vap}}$	fractional masses of the liquid and vapour phases in the cavitated system, respectively ()
γ	surface tension (psi-in)
r_c	meniscus radius (in)

recovery of hydrocarbons from such reservoirs is much more challenging compared to a conventional reservoir. Hydraulic fracturing improves the overall flow characteristics of an unconventional reservoir by increasing the surface area through which the fluid can escape from the interior of the formations, and thus, enhances the recovery of hydrocarbons from such reservoirs.

Operationally, the process of hydraulic fracturing involves injecting a fracturing fluid (which often includes a proppant blended with water and other chemical additives) into a confined space in the interior of a reservoir formation, as schematically shown in Fig. 1. Prior to the onset of steady state fracture propagation, the injection pressure monotonically increases with injected fracturing fluid volume. Once the pressure reaches a value that is high enough to overcome the material strength and confining stress, a fracture is nucleated in a direction perpendicular to the direction of minimum *in situ* compressive stress [3,4]. Mechanistically, hydraulic fracturing involves a nonlinear coupling between several complex processes (see Bunger et al. [5]; Adachi et al. [6], Clifton et al. [7]), including (1) flow of the fracturing fluid within the fracture, (2) flow of the pore fluid and seepage (leak-off) of fracturing fluid, (3) deformation of a porous medium induced by both the hydraulic pressurization of the fracture and the compression/expansion and transport of pore fluid within the pores, and (4) fracture propagation *via* subsequent damage of the material. Because of a strong nonlinear coupling between these processes, obtaining a mathematical solution to the problem of a fluid-driven fracture in a poroelastic medium requires solving a nonlinear system of integro-differential equations. This system includes the equations of equilibrium, the equations of poroelasticity governing matrix deformation and the associated fluid diffusion in the matrix, the lubrication equations governing the fluid flow within the fracture, and the constitutive equations governing the deformation and damage of the rock along the fracture.

Typically, in poroelastic solids, a mechanical deformation is accompanied by an adjustment in pore pressure due to flow of the pore fluid between pores [28,28]. This pore pressure adjustment prevents build-up of large gradients in pore pressure within the material. The fluid flow between pores is predominantly Darcy flow and is primarily dictated by the intrinsic