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Simulation of proppant transport with gravitational settling and fracture closure in a three-dimensional hydraulic fracturing simulator

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ABSTRACT

We implement proppant transport in a three-dimensional hydraulic fracturing simulator, including proppant settlement due to gravity, tip screen-out, and fracture closure. Constitutive equations are used that account for processes that can cause the flowing fraction of proppant to be different from the volumetric fraction of proppant. The constitutive equations capture the transition from Poiseuille flow to Darcy flow as the slurry transitions from dilute mixture to packed bed. We introduce new constitutive equations that allow the simulator to seamlessly describe the process of fracture closure, including a nonlinear joint closure law expressing fracture compliance and roughness and accounting for the effect of proppant accumulation into a packed layer between the fracture walls. We perform sensitivity analysis simulations to investigate the effect of fluid viscosity, proppant density, proppant size, and formation permeability. The simulations confirm that tip screen-out can limit fracture length, cause proppant banking, and increase injection pressure. Sensitivity analysis indicates that reasonably accurate results can be achieved without excessive mesh refinement. We also perform a simulation of hydraulic fracture propagation through a complex natural fracture network. In this simulation, proppant tends to accumulate at the intersections between natural and hydraulic fractures. Overall, the results suggest that in very low permeability formations, proppant settling is a major problem for proppant placement because proppant tends to gravitationally settle before fracture closure can occur. Because leakoff is so slow, proppant immobilization through bridging is critical for vertical proppant placement. Bridging can occur at aperture approximately three times greater than particle diameter, which will occur much sooner after shut-in than full mechanical closure. Even though larger diameter proppant settles more rapidly, it may lead to better proppant placement because it will bridge sooner, at a larger fracture aperture. These results also suggest that it is critical to optimize injection schedule in order to avoid tip screen-out, which leads to a shorter, wider fracture in which bridging is less likely to occur. Our modeling approach can be used practically for optimization of proppant placement through selection of fluid properties, proppant properties, and injection schedule.

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1. Introduction

Hydraulic fracturing is performed by injecting fluid into the subsurface at high rate and pressure, opening and propagating fractures through the formation. In the majority of fracturing treatments, particulate matter called proppant is pumped in a slurry with the injection fluid. After injection is stopped, fluid pressure decreases, and the fractures close. The proppant holds the fractures open and increases their ability to conduct fluid after closure.

Several approaches have been used for numerical simulation of fluid–solid two-phase systems, such as proppant slurry. The two most common frameworks are Eulerian–Eulerian and Eulerian–Lagrangian (Hu et al., 2001; Zhang and Chen, 2007; Tsai et al., 2012). In the Eulerian–Eulerian technique, the particles and fluid are both treated with an Eulerian framework. Each component is governed by conservation equations in stationary control volumes (Clifton and Wang, 1988; Ouyang et al., 1997; Mobbs and Hammond, 2001; Adachi et al., 2007; Weng et al., 2011; Dontsov and Peirce, 2015). In the Eulerian–Lagrangian technique, proppant transport is described with a Lagrangian framework, which tracks the locations of individual particles or groups of particles, and fluid flow is described with an Eulerian framework (Tsai et al., 2012; Tomac and Gutierrez, 2015).

For describing slurry flow, it is necessary to calculate an

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Nomenclature

A_s	fracture surface area (m^2)
BHP	bottomhole pressure (MPa)
c_f	fluid compressibility (MPa^{-1})
c_p	pore volume compressibility of the part of the aperture filled with proppant (MPa^{-1})
c_t	total compressibility of the matrix (MPa^{-1})
c_ϕ	porosity compressibility of the matrix (MPa^{-1})
C	Carter leakoff coefficient ($m/s^{1/2}$)
d	proppant diameter (m)
D	cumulative sliding displacement (m)
D_b	term related to the permeability of the packed particles (–)
E	aperture (m)
$E_{hf\ \max,resid}$	maximum value of residual aperture of hydraulic fracture (m)
E_0	residual fracture aperture (m)
E_{open}	part of the mechanical separation between walls of an open element (m)
E_p	part of the mechanical separation between walls of an open element (m)
g	gravitational acceleration (m^2)
G	shear modulus (MPa)
G_p, G_s	numerical function (–)
$\bar{G}_p$	function controlling proppant flow due to gravity (–)
h	maximum fracture height (m)
k	fracture permeability (m^2)
k_{leak}	formation permeability (m^2)
K_{Ic}	fracture toughness ($MPa\ m^{1/2}$)
N_{max}, N_{min}	number of proppant particles (–)
P	fluid pressure (MPa)
P_0	initial fluid pressure (MPa)
ΔP	differential pressure (MPa)
$q_{f,flux}$	fluid mass flux (mass flow per cross-sectional area) (kg/m/s)
$q_{p,flux}$	proppant mass flux (mass flow per cross-sectional area) (kg/m/s)
q_{leak}	fluid mass leakoff rate per fracture surface area (kg/m/s)
Q_p, Q_s	function numerically calculated (–)
$\bar{Q}_s$	function representing effective viscosity and transition of flow (–)
$\bar{Q}_p$	function controlling flowing volume fraction of proppant in pressure-driven flow (–)
Q_{tot}	total volume of fluid injected (m^3)
R_A, R_{B1}	dimensional residual of stress equations (MPa)
R_{B2}, R_C	dimensional residual of stress equations (kg/m^3)
$R_{d,A}$, $R_{d,B1}$, $R_{d,B2}$, $R_{d,C}$	dimensionless residual of each equation (–)
R_f	mass balance error of fluid (kg)
Re	Reynolds number (–)
s_f	source term of fluid ($kg/m^2/s$)
s_p	source term of proppant ($kg/m^2/s$)
S	ratio of proppant immobilization time to settling time (–)
S_0	fracture cohesion (MPa)
t	time (s)
t_{immob}	estimated time of fracture closure (s)
$t_{settling}$	estimated time of proppant settling (s)
T	fracture transmissivity (m^3)
v_s	sliding velocity (m/s)
$v_{settling}$	settling velocity (m/s)
V_{sh}	shock velocity (kg/m/s)
V_w	wellbore volume (m^3)
Δx	element length (m)
β	constant (–)
δ_i	variable used for adaptive time step (various units)
ε_A, ε_{B1}, ε_{B2}, ε_C, ε_{D1}, ε_{D2}, ε_{D3}	tolerance of each system of equations (–)
η	radiation damping coefficient (MPa/(m/s))
η_{targ}	one fourth of a user specified tolerance for change in a variable, used for adaptive timestepping (–)
μ	fluid viscosity (MPa s)
μ_f	coefficient of friction (–)
ρ_f	fluid density (kg/m^3)
ρ_{f0}	initial fluid density (kg/m^3)
ρ_p	proppant density (kg/m^3)
σ_n	normal stress (MPa)
σ_n'	effective normal stress (MPa)
$\sigma_{n,ref}$	effective normal stresses required to cause a 90% reduction in aperture (MPa)
$\sigma_{n,ref,\max}$	user-defined maximum value of $\sigma_{n,ref}$ (MPa)
$\sigma_{n,ref,\min}$	user-defined minimum value of $\sigma_{n,ref}$ (MPa)
ς_A, ς_B	user-defined reference normal stress (MPa)
σ_{xx}	initial principal stress in the x-direction (MPa)
σ_{yy}	initial principal stress in the y-direction (MPa)
τ	shear stress (MPa)
ν	Poisson's ratio (–)
φ	volume fraction of proppant (–)
φ_m	maximum volume fraction of proppant (–)
$\bar{\varphi}$	normalized proppant concentration (–)
ϕ	formation porosity (–)
χ	blocking function (–)
ω	factor for adaptive timestep (–)
Pe	Péclet number (–)
∇	gradient operator (m^{-1})

effective fluid viscosity (Adachi et al., 2007). The earliest major contribution on this topic was the theory of dilute suspensions of particles (Einstein, 1905). For concentrated suspensions of particles, one of the simplest expressions was introduced by Mooney (1951). For the modeling of proppant transport, an expression similar to the Krieger–Dougherty equation (Krieger and Dougherty, 1959) is usually used (Adachi et al., 2007). In this study, we follow the method of Dontsov and Peirce (2014), who used the constitutive model introduced by Boyer et al. (2011), which is described below.

The slip velocity vector expresses the difference in average velocity between the particles and fluid. There is a tendency for transverse particle migration away from the fracture walls, where shear stress is maximum, to the center of the flow channel, where shear stress is lowest. This phenomenon causes higher proppant concentration at the center of channel, where fluid velocity is highest (Constien et al., 2000). Some models assume that proppant distribution is uniform across the aperture, and so the velocity difference between fluid and proppant is caused only by gravity (Adachi et al., 2007). Other models account for proppant migration away from the fracture walls to the center of the flow channel. Mobbs and Hammond (2001) performed simulations of proppant transport taking into account the migration effect with an assumed proppant distribution across the aperture. Boronin and Osiptsov (2014) performed a similar analysis with a different assumed particle distribution and achieved good agreement with

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