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Simulation of the transport and placement of multi-sized proppant in hydraulic fractures using a coupled CFD-DEM approach

Guodong Zhang [a,b,*], Mingzhong Li [a], Marte Gutierrez [b,*]

[a] College of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, China
[b] Department of Civil and Environment Engineering, Colorado School of Mines, Golden, 80401, USA

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ABSTRACT

The productivity of fractured wells is mainly governed by propped fractures, so it is of significant importance to find out where the injected proppants go during hydraulic fracturing treatments, as this is essential to scheduling proppant injection in fracturing design. Using a coupled CFD-DEM model, the transport and placement of multi-sized proppants in fractures in vertical and horizontal wells were systematically investigated, and the effects of having multi-sized particles relative to uniformly-sized ones on the proppant placement were quantitatively characterized. When a proppant-laden fluid is injected into a fracture in vertical wells, a small proppant bank quickly forms. The injected large and small proppant particles are almost uniformly mixed, with just a small-proppant region at the back side of the bank. In comparison in horizontal wells, a proppant dune first forms near the wellbore in a fracture, and the large proppant particles are more likely to accumulate near the wellbore while the small particles are transported deeper into the fracture. The main transport mechanisms of proppant particles are settlement and fluidization, which cause a three-layer flow pattern (stationary proppant bed, fluidization layer and clean fluid layer) to form. In addition, vortex is also an important proppant transport mechanism, especially in a fracture in horizontal wells, where the vortex drags the injected proppant particles to different locations causing a dual-dune profile. The effect of fracture tip screen-out on the proppant placement was investigated. Screen-out can significantly change the flow field in a fracture and this will subsequently affect final proppant placement. Ultimately, the process of graded proppant injection was realistically modeled, which shows small proppants to be transported deeper into the fracture, while large proppants accumulate near the wellbore.

1. Introduction

Coupled particle-fluid flows are ubiquitous in many nature and industrial processes. Typical examples include fluidization bed, sand transport in rivers and lakes, waste water discharge and pneumatic conveying of granular materials, etc. In oil industry, proppants are usually injected into the hydraulic fracture during hydraulic fracturing treatments to prevent the fracture from closing [1,2]. Because the productivity of fractured wells is mainly governed by propped fracture, the placement of injected proppants in a fracture greatly affects fracturing efficiency [3]. From its first use in hydraulic fracturing, the processes of proppant transport and placement in a fracture has remained, for the most part, poorly understood [4]. Proppant transport mechanisms, slurry flow pattern and multi-sized proppant distribution in a fracture driven by thinning fracturing fluids remain as topics of active research.

The transport of proppant-fracturing fluid slurry in a fracture can be treated as particle-fluid mixture flows between two parallel plates, so slot experiments are commonly employed to investigate proppant transport and placement in a fracture [5,6]. However, compared with experimental studies, the development of numerical analysis of particle-fluid mixture flow is relatively slow due to the big challenge of modeling the interaction of particles with fluid and particles with particles. Single-phase models were first proposed, wherein the mixture was assumed to be a viscous incompressible fluid with density and viscosity as a function of the particle volumetric concentration [7–9]. However, when particles are transported by thin fluids, the particles will quickly settle out of the fluid, so single-phase models are inappropriate in this

* Corresponding authors at: 308 Coolbaugh Hall, 1012 14th St., Golden, CO 80401, USA. Fax: +1 303 273 3602.
E-mail addresses: zhangguodong@mines.edu, zhang_gd1987@hotmail.com (G. Zhang), limzh@upc.edu.cn (M. Li), mgutierr@mines.edu (M. Gutierrez).

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Nomenclature

C_d	turbulent drag coefficient
d	particle diameter (m)
d_m	particle median diameter (m)
$d_{\max}$	maximum diameter of multi-sized particles (m)
$d_{\min}$	minimum diameter of multi-sized particles (m)
$\vec{f}_b$	particle body force per unit volume (N)
$\vec{f}_{drag}$	drag force applied to each individual discrete particle (N)
F_i^c	contact force (N)
h	fluid cell size (m)
H_M	equilibrium height of the bank for multi-seized particles (m)
H_U	equilibrium height of the bank for uniformly-seized particles (m)
i	index of the two contacting particles (i = 1, 2)
K_n	normal stiffness at the contact (N/s)
K_s	shear stiffness at the contact (N/m)
M_i^c	is particle momentum at the contact (kg·m/s)
p	fluid pressure (Pa)
Re_p	particle Reynolds number
S	distance between two particles (m)
t	time (s)
$\vec{u}$	average velocity of all particles in a given fluid element (m/s)
$\vec{U}$	average relative velocity between particles and fluid (m/s)
$\vec{v}$	fluid velocity (m/s)
v_{inj}	fluid injection velocity (m/s)
V	characteristic velocity (m/s)
V_n	relative normal velocity at the contact (m/s)
V_s	relative shear velocity at the contact (m/s)
V_f	falling velocity (m/s)
w	fracture aperture at the location of fracture screen-out (m)
W	fracture aperture near the wellbore (m)
x_0	location of the contact point
x_i	center position of particle i

Greek symbols

β	a coefficient
γ_n	critical normal damping ratio
γ_s	critical shear damping ratio
δ_n	overlap defined to be the relative contact displacement in the normal direction (m)
δ_s	overlap defined to be the relative contact displacement in the shear direction (m)
ε	porosity
ε_p	particle volumetric concentration
θ_{inj}	injection angle (°)
θ_s	settling angle (°)
μ	fluid dynamic viscosity (Pa·s)
ρ_f	fluid density (kg/m^3)
ρ_p	particle density (kg/m^3)
τ	characteristic time (s)

circumstance. Mixed phase models were presented to simulate particles and fluids as separate entities. There are two methods to model particle flow: the continuum approach at a macroscopic level and the discrete approach at a microscopic level, and fluid flow can be modeled at different time and length scales from discrete to continuum [10]. Two popular combinations of the two-fluid model (TFM) and computational fluid dynamic (CFD)-discrete element method (DEM) are commonly used to describe particle-fluid flow. In TFM, both fluid and particle are treated as interpenetrating continuum media. Taking the gravitational settling into account, Dontsov and Peirce [11], and Shiozawa and McClure [12,13] modeled particle transport in a fracture, and uneven particle distribution was observed. In CFD-DEM, the interactions between fluid and particles were accounted for to model particle-fluid mixture flow using an Eulerian–Lagrangian method [14–16]. DEM [17,18] is used to describe particle-particle interaction, which is represented with frictional, inelastic contact force, and to trace the trajectories of individual particles. This is the key requirement to investigating particle micro-hydrodynamic and micro-mechanical behavior. Tomac and Gutierrez [19] introduced a new particle contact model coupled in DEM and investigated the micro-mechanical behavior of particles in a narrow channel. Blyton et al. [20] modeled the motion and placement of proppant particles in a fracture using a coupled CFD-DEM code.

Although proppant transport in a fracture was widely modeled, all of the particles used in previous studies were uniformly-sized. However, proppants are multi-sized particles with a wide range of diameters, which may significantly affect their transport and placement in a fracture. When the proppants are injected into a fracture, the large and small particles can interact with each other, and then the vertical and horizontal transport of the injected proppants will be affected. For multi-sized particle suspensions, the large particles will settle faster than the small ones, and sedimentation will start with the formation of a series of interfaces within the suspensions. Dynamic sorting due to interaction of the various grain-size populations plays an important role on the vertical particle distribution [21,22]. For horizontal flow of multi-sized particulate slurry, the large particles also will accumulate near the bottom of the channel, while the small ones are more likely to be suspended [23–25]. Therefore, when the multi-sized proppants are injected into a fracture, they will settle at different locations, causing different proppant placements.

Ultimately, it is of significant importance to investigate where the injected multi-sized proppants will occupy in a fracture, which will eventually affect the fracture conductivity and fracturing efficiency. Knowledge of proppant transport and placement is very helpful for scheduling proppant injection strategies in fracturing design. As stated previously, to the best of our knowledge, no work has focused on the transport and placement of multi-sized proppants in a fracture particularly at the particle scale. In this work, a coupled CFD-DEM approach is used to fill this knowledge gap. The effect of fracture tip screen-out on the proppant placement is investigated, and the process of graded proppant injection are simulated and investigated in this paper.

2. Numerical model

For particle-fluid mixture flow, the flow of the particle and fluid phases are strongly coupled via momentum exchange. Due to settlement of the injected proppants in a fracture and the relative motion between large and small proppants, proppant interaction is important and must be taken into account. In this section, the fluid flow modeling, fluid-particle coupling scheme, and models

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