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# A coupled CFD-DEM approach to model particle-fluid mixture transport between two parallel plates to improve understanding of proppant micromechanics in hydraulic fractures

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ABSTRACT

Computational Fluid Dynamics coupled with Discrete Element Method (CFD-DEM) was used in this paper to model particle-liquid mixture transport between two parallel plates to improve the understanding of proppant micromechanics in a hydraulic fracture. The linear spring-dashpot model was used to model contact behavior between the particles in DEM code, and the interaction between the particles and fluid was coupled in the CFD code in terms of volumetric porosity and coupling force. The flow patterns and particle transport mechanisms were investigated based on which four developmental stages were divided from the beginning of injection to the formation of the final particle bank. The results show that when particles are transported in a thin fluid, they will quickly settle out of the fluid and accumulate at the bottom forming a particle dune. As the dune height increases, the flow stream is gradually hindered by the dune, and then the injected particles are vertically lifted and settle at the front of the dune. When the equilibrium height of the dune is reached, the dune develops to a bank, and then the particles injected later overshoot the bank and settle at the back side of the bank. The dune shape is significantly influenced by the erosion caused by the transported particles and flowing fluid, and the flow patterns of three-layers and two-layers are observed in different stages. Three particle transport mechanisms of settlement, fluidization and suspension, previously presented in early experimental studies, are observed in the CFD-DEM simulations. A new important transport mechanism of vorticity is also observed, which can control the motion direction of the injected particles during earlier and later injection stages.



## 1. Introduction

Transport of particles driven by fluids exists in a wide variety of natural processes and engineering applications. Typical examples include river sand transport, wastewater discharge, fluidized bed and pharmacy granulation, *etc.* In petroleum engineering, hydraulic fracturing technology has been widely used for decades to extract hydrocarbons. During the hydraulic fracturing treatments, high pressurized liquid is injected to initiate and propagate fracture, and when the fracture is created, proppant-laden fluid is pumped to keep the facture open and allow it to maintain significant conductivity after fracturing fluid pressure is reduced [1]. The transport behavior of proppant particles in a fracture controls its terminal placement form, which has a dominant effect on well productivity. Therefore, prediction of proppant placement is of significant importance to fracturing design and post-analysis. However, since proppant is first used in hydraulic fracturing, the question of proppant transport and placement in fractures has remained, for the most part, unanswered [2].

For conventional fracturing fluids, most of the proppant particles remain in suspension until the fracture closure, while the proppant rapidly settles out of suspension in thin fracturing fluids forming a dune at the bottom of the fracture. Due to the advantages of the low cost and small reservoir damage, slickwater fracturing fluid is widely used to economically develop unconventional resources (shale gas, tight gas, coal-bed methane, etc) [3]. It is estimated that >80% of the fracturing fluids used in hydraulic fracturing treatments in the United States are slickwater [4]. However, the viscosity of slickwater is very low with minimal chemical additives, and its capability to transport proppant is significantly reduced. When proppants are transported in such thin fracturing fluids, the transport mechanisms are totally different from those in conventional fracturing fluids [5].

Numerous experimental research reported over the years has greatly contributed to the understanding of the proppant flow and transport process in thin fracturing fluids [6–8]. The first experiment on sand-water slurry transport in a slot was carried out by Kern et al. [9]. Additionally, the STIM-LAB consortium has been collecting data on proppant

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## Nomenclature

*Symbols*

| | |
|---|---|
| $C_d$ | turbulent drag coefficient |
| $d$ | particle diameter (m) |
| $\vec{f}_b$ | particle body force per unit volume (N) |
| $f_c$ | friction coefficient at the contact |
| $\vec{f}_{drag}$ | drag force applied to each individual discrete particle (N) |
| $F_i^c$ | contact force (N) |
| $\lvert F_i^n \rvert$ | normal contact force (N) |
| $\lvert F_i^s \rvert$ | shear contact force (N) |
| $F_{\max}^s$ | maximum allowable shear contact force (N) |
| $f_p$ | particle surface friction coefficient |
| $f_w$ | wall friction coefficient |
| $h_c$ | height of fluid cell (m) |
| $H_e$ | equilibrium height of particle mound (m) |
| $i$ | index of the two contacting particles ($i = 1, 2$) |
| $K_n$ | normal stiffness at the contact (N/s) |
| $k_{npi}$ | particle normal stiffness (N/s) |
| $k_{nw}$ | wall normal stiffness |
| $K_s$ | shear stiffness at the contact (N/m) |
| $k_{spi}$ | particle shear stiffness (N/s) |
| $k_{sw}$ | wall shear stiffness |
| $m$ | effective system mass (kg) |
| $M_i^c$ | is particle momentum at the contact (kg·m/s) |
| $p$ | fluid pressure (Pa) |
| $\mathrm{Re}_p$ | particle Reynolds number |
| $t$ | 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) |
| $V_f$ | settling velocity (m/s) |
| $V_n$ | relative normal velocity at the contact (m/s) |
| $V_s$ | relative shear velocity at the contact (m/s) |
| $x_0$ | location of the contact point |
| $x_i$ | center position of particle $i$ |

*Greek symbols*

| | |
|---|---|
| $\beta$ | a coefficient |
| $\gamma_n$ | critical normal damping ratio |
| $\gamma_s$ | critical shear damping ratio |
| $\delta_n$ | overlap defined to be the relative contact displacement in the normal direction (m) |
| $\delta_s$ | overlap defined to be the relative contact displacement in the shear direction (m) |
| $\varepsilon$ | porosity |
| $\varepsilon_p$ | particle volumetric concentration |
| $\theta$ | settling angle (°) |
| $\mu$ | fluid dynamic viscosity (Pa·s) |
| $\rho_f$ | fluid density (kg/m$^3$) |
| $\tau$ | characteristic time (s) |

transport in slots for >20 years [6]. Previous experimental results show that a proppant bank first forms near the wellbore in thin fracturing fluids, and the proppant that is pumped later will overshoot the previously-pumped proppant and will settle on the back side of the bank. Fig. 1 shows a schematic diagram demonstrating the experimental slot findings. Due to the existence of the proppant bank, a three-layer flow pattern has been proposed for proppant-laden fluid flowing in fractures [6,7,10]. At the bottom of the fracture is an immobile stationary bed, above which is a moving bed like a "traction carpet", and at the top of a fracture is a clean fluid layer.

Mack et al. [11] thought if proppant particles have sufficient momentum, they will bounce onto the bed with sufficient force to kick other particles up into the flow stream. Three primary proppant transport mechanisms with a bank were proposed as shown in Fig. 2, namely: (1) Surface creep: when the proppant-laded fluid flows across the top of the bank at a flow rate higher than the critical starting velocity, proppant particles will roll or slide along the surface of the settled proppant bank; (2) Saltation: as the flow rate increases, parts of the proppant particles are lifted off the bank and travel downstream before falling back and being re-suspended; and (3) Suspension: When the flow rate exceeds the critical suspension velocity, some proppant particles are suspended and transported with liquid.

Patankar et al. [6] considered that lift force plays a central role in particle suspension in channel flows and proposed that a more efficient particle transport mechanism was fluidization by lift. Once the equilibrium height is achieved, proppant transport in the slot is primarily governed by fluidization and sedimentation [5,12]. Fluidization of proppant particles occurs when fluid turbulence "lifts" the particles off the stationary bed, while sedimentation occurs as these fluidized particles are washed or dragged across the top. For a high flow rate, a high turbulence regime at the top of the bank creates an eddy, which makes the proppant particles travel in a circular motion back toward the bank [3].

Although slot flow experiments have been reported for decades, there has been relatively little theoretical analysis of the results [11]. The transport behavior of single particle between two parallel walls has been widely studied [13–16], but for particle-liquid mixture flow, the interaction between particles plays a crucial role, which makes it to be a large challenge to model the mixture transport [17]. Effective-fluid approximation is presented in early models, where the slurry is assumed to be viscous incompressible fluid with density and viscosity depending on the particle volumetric concentration [18–20], and then a uniform particle distribution across the fracture is commonly considered [21]. Taking into account mixture dynamics governed by micro-level particle fluctuations in a high-shear-rate flow, a non-Newtonian particle-liquid mixture flow in fracture was modeled by Eskin and Miller [22], and non-uniform particle distribution was obtained. For particle transport in thin fluids, settlement behavior becomes pronounced and cannot be negligible, which could significantly affect the flow pattern in a channel. An unsteady laminar suspension flow in a vertical hydraulic fracture subject to gravity acceleration was established by Daneshy [23], and Boronin and Osiptsov [24]. Dontsov and Peirce [17,25,26] modeled proppant transport with gravitational settling in hydraulic fractures and a non-uniform particles distribution across the channel was obtained. Recently, a two-layer model (mixture and proppant bed) was presented by Shiozawa and McClure [27] to describe proppant transport in a two-dimensional discrete fracture network model. They neglected the proppant-free zone and assumed a uniform concentration of mixture within an element and no proppant transport within the bed.

Actually, most models that predict proppant transport in fracture focus on simulated pressure and concentration profiles, and the interactions between fluid and proppant are normally ignored [28]. The Eulerian-Lagrangian method is commonly used to fully account for the particle-liquid interaction, and the numerical technique solves the governing equations of the fluid phase using a continuum model and those of the particle phase using a Lagrangian model [29–31]. In addition, for the flow of dense particle-liquid mixtures, collisions between particles-particles and between particles-walls become more frequent, and their effects on the flow field cannot be neglected. Based on a user-defined particle contact model which accounts for lubrication effects due to the formation of a thin layer surrounding a particle, Computational Fluid Dynamics coupled with Discrete Element Method (CFD-DEM) was used by Tomac and Gutierrez to improve the understanding of the micro-mechanical behavior of particles in a channel [32]. The