Proppant Flow and Transport in a Narrow Fracture in Turbulent Flow Regime

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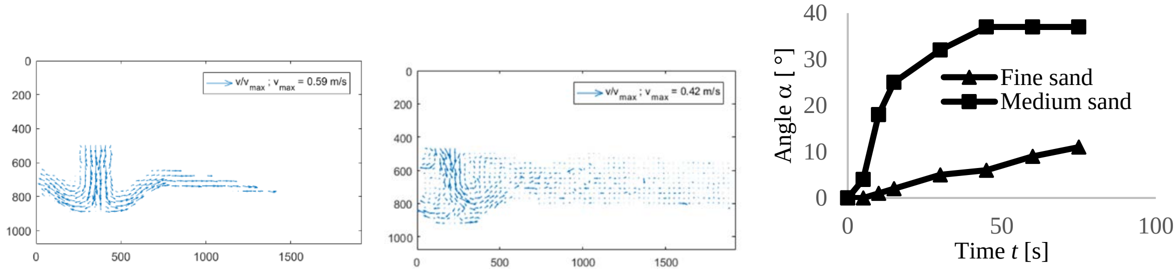
Introduction

This paper presents a new experimental research and evaluation of turbulent flow of proppant and fluid slurries in narrow and smooth fractures. Proppant is small granular material which is introduced in hydraulic fractures to keep them open for a long-term geo-reservoir function. Proppants are used in geothermal reservoirs where enhancing of the permeability relies on tensile fracture propagation and shearing of existing fractures is not a dominant mechanism. Such georeservoirs have perspective in sandstone geological formations or on the boundary between sedimentary and igneous rock masses. Laboratory experiments are performed using Plexiglas and 3D printed narrow fracture zones. A progressive cavity pump injects proppants mixed with carrying fluids in varied volumetric concentrations, flow rates and fluids. Several different sand proppants are used. The research results indicate that turbulence is a decisive factor in progression of the slurry into a fracture system. However, turbulent motion of dense particle phase slurries has not yet been well understood. Smaller particles respond well to higher flow rates and are carried over the bed of proppant in turbulent swirls. Therefore, the slurry consisting of smaller sand particles does not form large proppant bed and is transported further into the fractur system. Previously, laboratory measurements in slot-flow models yielded the minimum fluid viscosity for successful proppant transport (Goel et al., 2002; Goel and Shah, 2001). Studies of the ratio of particle diameter to the slot cell width provided estimates of the particle retardation velocities and clogging of proppant (Barree and Conway, 1995; Novotny, 1977; Patankar et al., 2002). When a proppant flows in a narrow channel, fluid velocity is different from proppant velocity, and some amount of the velocity retardation is present. Experimental observations of interactions between proppant particles in the flow revealed that hydrodynamic forces dominate at low proppant concentrations, while inter-particle interactions become a dominant factor at higher concentrations (Shah, 1982). Experiments in a vertical-slot flow demonstrated that proppant particles follow erratic paths, but do not scratch or touch the slot walls (Sievert et al., 1981). Proppant packs, which exhibit significant grain-to-grain contact, usually lead to clogging and screen-out events. A proppant pack forms within a fracture and can grow in any directions, with the fluid flowing on either side of the proppant pack (Daneshy, 2005). The laboratory studies (Novotny, 1977) of proppant concentration and bridging effects on proppant flow, as well as corresponding numerical simulations (Daneshy, 1978), provide some practical guidelines for avoiding particle bridging. Particle agglomerations occur as a result of fluid lubrication forces in a constrained flow and transport of dense slurries (Luo and Tomac, 2018, 2017, 2016; Tomac and Luo, 2016). Fundamental qualitative and quantitative theories for estimating whether the particle-fluid coupling is dilute or dense are given in the literature (Crowe et al., 2011). The prediction of the slurry particle-fluid coupling is based on the comparison between the average response time of particles to the fluid drag and particle collisions. A major objective of this study is to better understand the role of fracture walls, particle concentrations and type and fluid properties on the regime of proppant flow and transport in a narrow fracture and to investigate the role of turbulence.

Proppant flow and transport in a narrow fracture

Our experimental setup is located at the UCSD. It consists of a progressive cavity pump with flow rate controlled with variable frequency drive, which are run by a 3-phase 1HP motor. Proppant is pumped into a narrow acrylic-aluminum slot 2 mm wide, 51 cm high and 150 cm long. The experiments are conducted with silica sand sieved to 20/40, 40/70 and 60/100 mesh sizes, corresponding to coarse, medium and fine sands. The slot is initially filled with water, to mimic a low viscosity fluid present in reservoir fractures prior to proppant slurry arrivals. For carrying fluid Newtonian fluids are used which are water and glycerol-water mixture. Videos of experiments were taken with 2 high-speed cameras with up to 1000 fps capability. Captured videos were analyzed using an open-source particle image velocity software (PIV) called GEO-PIV and specially developed for studying geotechnical materials including sand (Take, 2015). Fig. 1 shows typical results of laminar and turbulent transport flow regimes of medium sand in water (a) and in higher viscosity glycerol-water slurry (b). Basic indices, which are typically used for evaluation of sediment transport in wider spaces like rivers and lakes, are calculated. The goal of this research is to evaluate validity and applicability of routine sediment transport indices for dense slurries flow and transport in narrow fractures. The results show only partial agreement, which means that the general trends were met, but the quantitative agreement was not achieved. The smaller the sand average grains are, as well as, the higher the fluid dynamic viscosity, more transport is achieved down the fracture length accompanied with the less steep dune. More slurry suspension was also observed with smaller particle sizes and higher fluid velocities. Particle Reynolds numbers (R_{es}) characterize the modeled flow experiments as settling or quasi-homogeneous flowing slurries, which was also observed in experiments. Rouse numbers indicate that complete slurry will be transported as a wash load, which was only partially observed for fine sand and medium sand in glycerol-water mixture. Both used indices do not incorporate injected concentration of particles, particle-particle interactions, or the effect of narrow fracture walls with particle-wall interaction forces. The dune is generally symmetric in all the cases. The dune form is however different for three different sands injected in a water slurry. Injection of coarse sand produced very steep triangle dune without further transport of particles except for some minor rolling down the dune. When the average sand particle size decreases, as well as R_{es}, dune spreads out in a different geometry (Fig. 2c). For the medium sand, the dune has *S* shape and significant resuspension and upslope motion of particles occurs. For the fine sand, particles are transported further in a fracture in a horizontal direction suspended over the bed. Financial support provided by the U.S. National Science Foundation, Division of Civil, Mechanical and Manufacturing Innovation under grant NSF CMMI 1563614 is gratefully acknowledged. The opinions expressed in this paper are those of the authors and not the NSF.



a) b) c)

Fig. 1: Experimental results for 40/70 mesh sand in water (a) and water-glycerol (b) fluids after *t*=20 s of injection and dune angle for fine and medium sand in water (c)

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