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Particle-Fluid Flow and Transport Between Rough Surface Boundaries

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Abstract This paper investigates effects of rough fracture wall surfaces on particle-fluid interactions and slurry settling velocity. Proppant particles are injected into fractures during hydraulic fracturing process of geo-reservoirs for maintaining open fractures after pressure shut-down. The propping open of the fracture provides enhancement of the hydraulically fractured geo-reservoir productivity and project yield. Part of the successful design of a proppant injection program is the ability to predict proppant settling behaviour accurately. Numerous past investigations of the injected proppant behaviour in fractures have involved idealized configurations in which the proppant is injected into smooth walled fractures. The idealized conditions are however non-reflective of in field rock fracture surfaces, which exhibit complex characteristics, including geometrically roughened surfaces. Understanding of surface roughness variances' impacts on proppant and fluid flow is essential for accurately predicting proppant behaviour and improving design projects. This research uses the Discrete Element Method coupled with computational fluid dynamics (DEM-CFD) for studying effects of fracture surface roughness via varied fractal dimension on proppant settling behaviour. Fracture surfaces, representative of those found in actual rock fractures, were numerically generated based on a recursive subdivision algorithm known as the 'Diamond-square midpoint displacement' method. This work provides an insight into the importance of fracture surface roughness analogous to actual rock surface characteristics when considering proppant behaviour in fractures and of the impact of geometrically rough boundary walls on particle-fluid settling behaviour in general.

1 INTRODUCTION

This paper investigates micromechanics of particle settling in the presence of rough wall, between two walls which represent a hydraulic fracture. This research contributes to better understanding of dense phase fluid-particle coupled settling. The application of this research is predominately to improve proppant flow and transport in georeservoirs. Proppants are small granular materials which are injected into newly formed hydraulic fractures during stimulations of geothermal, oil and gas reservoirs. Proppants keep fractures open against large in-situ stresses which tend to close newly formed fractures after pumping and fracking is over. Numerous works have been performed in the past in studying single phase fluid behaviour in rock fractures. Brown performed 2-D finite difference computations of fluid flow through synthetically generated computer representations of fracture surfaces to determine the effects of surface roughness on flow [1]. This work concluded that the most influential factor in flow of fluid in fractures was the mean separation between the surfaces and root-mean square of surface height. He concluded that at larger separations, the surface topography had negligible effects on flow. In numerical evaluation work performed by Tsang it was concluded that combined effects of fracture roughness and tortuosity can lead to a decrease flow rate in a fracture. Further, his calculations showed that the effects of path tortuosity in depressing the flow rate in a rock fracture varied with the roughness characteristics of the rock fracture [2]. In cases in which fractional contact area was over 30%, the combination of effects from tortuosity and roughness led to a two to three orders of magnitude reduction in flow [2]. Both above studies illustrate the shortcomings of past assumed flow behaviour analogous to a parallel plate model, as had been previously implemented in rock fracture flow evaluations.

The evaluation of flow is further complicated by the inclusion of a particle solids phase in addition to the fluid, as is the case for proppant injection procedures. Early investigation into rough-wall effects on proppant settling rates was performed by Novotny [3]. Experimentation in that work was performed utilizing smooth-walled, Lucite slot fracture models as well as rough wall slot fractures which incorporated fractured carbonate rock. Slot widths tested included 0.125 inch (3.175 mm), 0.25 inch (6.35 mm), and 0.75 inch (19.05 mm). Proppant sizes were 10/20 sand and 20/40 sand. Experimental fluid was a non-Newtonian brine/oil emulsion with varying concentration of gelling (power-law fluid consistency index and power-law index ranges at 200 ^{o}F; 0.81 to 27.0 poise and 0.81 to 0.50 poise, respectively). It was illustrated in this work that the proppant incurred settling velocity retardation due to wall proximity effects relative to the mean proppant particle diameter. Novotny further concluded that the roughness of the fractured rock walls did not affect settling velocity differently than that observed in smooth wall fractures. He proposed that attenuated settling velocity could be described overall by the below formulations that depended on the opening width between fracture walls and the particle diameter:

$$\frac{v_w}{v_t} = 1 - 0.6526\frac{D}{W} + 0.147\left(\frac{D}{W}\right)^3 - 0.131\left(\frac{D}{W}\right)^4 - 0.0644\left(\frac{D}{W}\right)^5 \quad (Re < 1) \qquad (1)$$

$$\frac{v_w}{v_t} = 1 - \left(\frac{D}{2W}\right)^{\frac{3}{2}} \quad (Re \geq 100) \qquad (2)$$

In which v_w = hindered velocity due to walls, v_t = terminal fall velocity for a particle in an infinite fluid, D = particle diameter, W = opening width between vertical wall faces, and Re = the settling particle Reynolds number ($Re = \frac{\rho_f D|\vec{u}-\vec{v}|}{\mu}$, where $\vec{u}$ is the fluid velocity, $\vec{v}$ is the particle velocity, and μ is the fluid's dynamic viscosity).

Liu and Sharma also performed a series of experiments on both smooth and rough wall slot fractures [4]. It was observed that there was substantial hinderance to the horizonal velocity in rough wall fracture experiments. Liu further noted that for experiments in which the particle settling rates were studied, that rough wall configurations displayed significantly lower settling rates than those with smooth walls for the same particle diameter to cell opening width ratio [5]. Wall effects on particle velocities were noted in both Liu and Sharma [4] and Liu [5] to also be increasingly significant as fluid viscosity was increased. These higher viscosities indicated more pronounced settling velocity reductions for even larger slot width to particle diameter ratios. Tomac and Gutierrez additionally performed numerical simulation investigations into the particle-particle and particle-wall interactions within narrow and rough fracture channels [6]. Findings for this work pointed similarly to increased influence of wall effects in rough walled fractures as fluid viscosity increased. Further, this work pointed out that for simulations in rough fractures with the highest fluid dynamic viscosity considered, 0.1 Pa·s, settling velocity was greatly underestimated by the Novotny's relationship.

Roy et al. performed both experimental and numerical evaluation of proppant settling behaviour in fluids for fractures with surfaces reproduced from fractured shale. In the numerical simulation work, progressively increased fracture roughness effects were studied by increasing the scaling of the fracture deviations from initial fracture geometry (in effect, an accentuation of geometric rough features). It was concluded that the vertical velocities were mostly unaffected by the surface roughness changes except at the highest increase to fracture roughness studied. This decreased velocity in the most geometrically rough sample is attributed to particle 'jamming' occurring within the simulated fracture [7]. Experimentally, settling speeds of particles and their volumetric concentrations were recorded at a 3-cm window at the centre of the experimental fracture for various frames of the recorded settling process. Results of these observations were compared to the settling velocity relationship proposed by Richardson and Zaki [8] that incorporates both particle concentration and wall attenuation effects on settling velocity. It was indicated that the Richardson and Zaki [8] equation notably overestimates the settling rate for the small volumetric concentrations captured during this experiment (approximately 12% maximum concentration studied as indicated in the data).

Huang et al. performed numerical modelling of proppant injection via computational fluid dynamics (CFD) [9]. Wall roughness in this work is incorporated as an applied drag force to flow near walls. Findings of this work indicate that there is a decrease in the horizontal velocity of proppant slurry due to roughness, resulting in a non-linear relationship with wall roughness height. Findings indicated a velocity decrease of approximately 25% for roughness heights 8 times that of the proppant size. Further it was concluded that there was also a decrease in vertical proppant setting rate which allowed for greater proppant carrying distance.

As can be concluded from the above works, agreement as to the effects of wall roughness have not reached a consensus. Given this, investigation in this paper has been performed to further understand the behaviours of proppant particles in roughened walled fracture environments.

2 METHODOLOGY

Experimental and numerical approaches are used to better understand effect and micromechanics of particle-fluid settling in a narrow fracture in the vicinity of the rough wall. Small laboratory experiments are analysed using Particle Image Velocimetry (PIV) method. Numerical model uses coupled Discrete Element Method with resolved method of computational fluid dynamics.

2.1 Laboratory Experiments

Fig. 1 shows a small laboratory experimental setup on 20 x 40 cm narrow fracture with average aperture of 2 mm, where the front part is a smooth plexiglass sheet and the back part is composed of 3D printed replica of a laboratory produced hydraulic fracture from a scan [10]. Sieved 20-40 mesh silica sand shown in Fig. 1a is used in the experimental study [11,12]. PIV method is used for tracking slurry and individual particle settling [13]. The PIV algorithm uses meshes of digital images in a sequence from a video recording, and the algorithm extracts displacement data from sequences of digital images. Velocity vectors are obtained by combining the spatial displacement over the time between two figure frames taken with high speed video camera. Fig. 2 shows and example of large and small meshes of digital images and extracted slurry settling displacements between two parallel slots.

2.2 Discrete Element Method Coupled with Computational Fluid Dynamics (DEM-CFD)

Resolved DEM-CFD method is utilized in this study for the simulation of dense particle concentration settling behaviour in fracture geometries. Resolved DEM-CFD method allows for the ability to model fluid interaction with solid particles by resolving the fluid’s influence on the interface of the particle surfaces. This differs from unresolved DEM-CFD methods in that particle fluid interaction is not based on empirical or analytic correlations. Utilization of the resolved CFDEM software package [14,15] was implemented in this study. Figure 3 illustrates the methodology for realization of solid particles within an immersed CFD mesh as implemented by the software and fluid interactions at the particle surfaces. More in depth explanation of the methodology and implementation can be found in Hager et al., [14] and Hager [15].

Generation of rough fracture surface to mimic actual rock characteristics based on fractal dimension is generated via an algorithm known as the “Diamond-Square” method that recursively refines a surface to introduce asperities based on a specified fractal dimension. This methodology is typically attributed to the work of Fournier, er al. [16]. Modification of the algorithm was implemented by way of limiting maximum out of plane asperity height (+/- 20 micron in this set of simulations) as to maintain a similar aperture to the comparative ‘smooth wall’ simulation domain also tested. Due to this modification, fractal dimension was checked after the generation of the surfaces by use of the method described by Qiu et al. [17] in order to confirm final fractal dimension of generated surface. Rock fractal dimensions can vary amongst different rock types even of similar type. Brown [1] indicated that typical rock surfaces’ fractal dimensions tend to fall between values of 2.0 and 2.5. Given this range, two fracture surfaces, of fractal dimensions 2.0 and 2.454, were generated and used in the simulations.

Figure 4 shows the initial conditions and geometries of the generated ‘rough’ and ‘smooth’ fractures. To conserve computational resources, a symmetric plane was utilized at the + Y domain interface. Simulated domain is of dimension 1 mm x 1 mm x 1 mm. Simulations were both ran with similar volumetric concentrations of particles, approximately 31.9%. A wall condition for the DEM portion of the simulation is not included at the - Z interface as to allow the particles to continuously settle through the domain. Further summarization of the simulation conditions and properties are indicated in Table 1.

3 RESULTS

3.1 Particle Settling Between Rough Walls

Fig. 5 shows comparison of experimental results of particle slurry settling in a 2 mm narrow slot between two parallel Plexiglas sheets representing a smooth fracture, and one rough fracture side. Results using particle settling without any induced flow are shown for two different Newtonian fluids, which are produced by mixing glycerol and water. Results are given for a span of different initial particle concentrations. It can be concluded that increasing the particle concentrations the settling velocity is on average larger, which was explained to be due promoted particle agglomerations [11]. Furthermore, it is shown that rough walls also enhance the settling of the slurry. For both fluids, higher settling velocities were obtained experimentally for a given concentration between one smooth and one rough wall compared to between two smooth walls. The results are compared to previous published relationships from larger slot experiments which predict different trends [18-20].

Computational simulations of two fractures, one with smooth wall interface and one with rough wall interface were also performed. Figure 6 shows near wall fluid cell 2D velocities at a slice through the middle of the simulation domains for the ‘smooth’ and ‘rough’ fractures. Fluid flow over the rough interface can be seen to have been more greatly dampened with less recirculation reintroduced back into the fluid domain away from the wall. Figure 7 shows the mean settling velocities of the simulated particles throughout the duration of the simulation. Average settling velocities for the particles after the initial instable particle behaviour from starting in a quiescent fluid state are additionally indicated. Figure 8 further shows the number of particles that have not settled out through the fluid and remain in the domain throughout the duration of the simulation. Increased settling velocity in rough wall configurations is observed in the velocity comparison as well as with the number of particles that have settled out of the domain.

4 CONCLUSIONS

This paper shows results of micromechanical experimental and numerical study to better understand particle-fluid interactions and settling behaviour in a narrow fracture near rough walls. Investigation combine PIV analysis method on physical experimentation and numerical simulation with resolved DEM-CFD. Specifically, focus was given to a single particle and average particle settling velocities in different fluids and initial concentrations, as well as, micromechanical investigation of the fluid motion near the wall in numerical model. Numerical and experimental results indicated similar effects of rough walls on fluid behaviour near the wall and fluid’s motion impact on particle behaviour, namely, the promoted particle settling rate in proximity of a geometrically rough wall. The findings of this study are in collisions with some of the previous experimental findings in wider slots, where inhibited particle settling occurred in the presence of the rough wall. This study observed retardation of fluid velocities along the rough wall and significant variations in fluid velocity vector directions caused by inclined wall surfaces. At the same time, average gravitational settling of particles was recorded to be faster than in the case with a rough wall boundary. Faster gravitational settling may be attributed to either agglomerations of particles due to the motion further from the wall caused by irregular fluid motion compared to near vertical wall, or to relative dominance of the gravity vs. retarded upwards fluid drag. It is important to note, that we did not observe effect of particle-wall collisions or interactions in our numerical study, which may cause decrease of particle settling velocity due to jamming observed previously.

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Table 1: DEM-CFD model properties and conditions.

Material Properties						**Model Conditions**	
Proppant Parameters:		**Units**	***Fracture Wall Properties:***		**Units**	***CFD Boundary Conditions:***	
Particle Diameter	250	μm	**Young's Modulus**	$50x10^6$	N/m^2	**+/- *X* faces, + *Y* face**	Slip
Particle Density	2600	kg/m^3	**Poisson Ratio**	0.425	-	**– *Y* face, +/- *Z* faces**	No-Slip
Contact friction value	0.2	-	**Shear Modulus**	$20x10^6$	N/m^2	**DEM Boundary Conditions:**	
Young's Modulus	$50x10^6$	N/m^2	***Fluid Parameters:***		**Units**	**+/- *X* faces, + *Y* face, + *Z* face**	Reflect
Poisson Ratio	0.3	-	**Dynamic Viscosity**	3	Cp	**-*Z* face**	Destroy
Coefficient of Restitution	0.425	-	**Density**	1000	kg/m^3	**- *Y* faces**	Wall
Coefficient of Restitution	0.425	-					

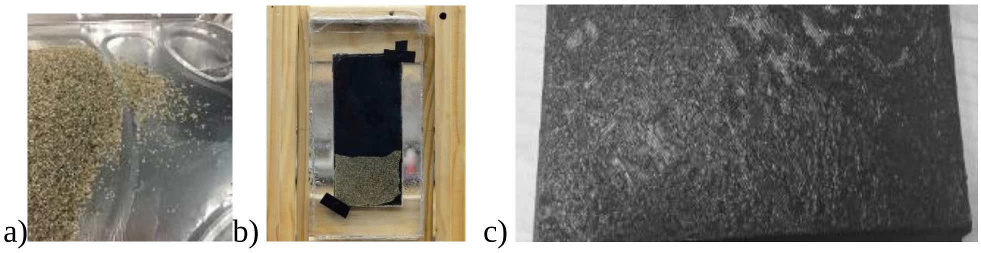


Figure 1: Experimental Setup a) 20-40 mesh sand, 200 x 400 x 2 mm narrow slot, 3D printed rough granite fracture [12].

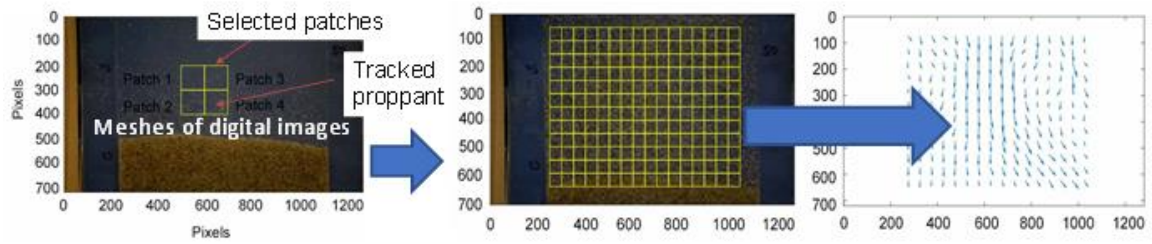


Figure 2: Particle Image Velocimetry [12].

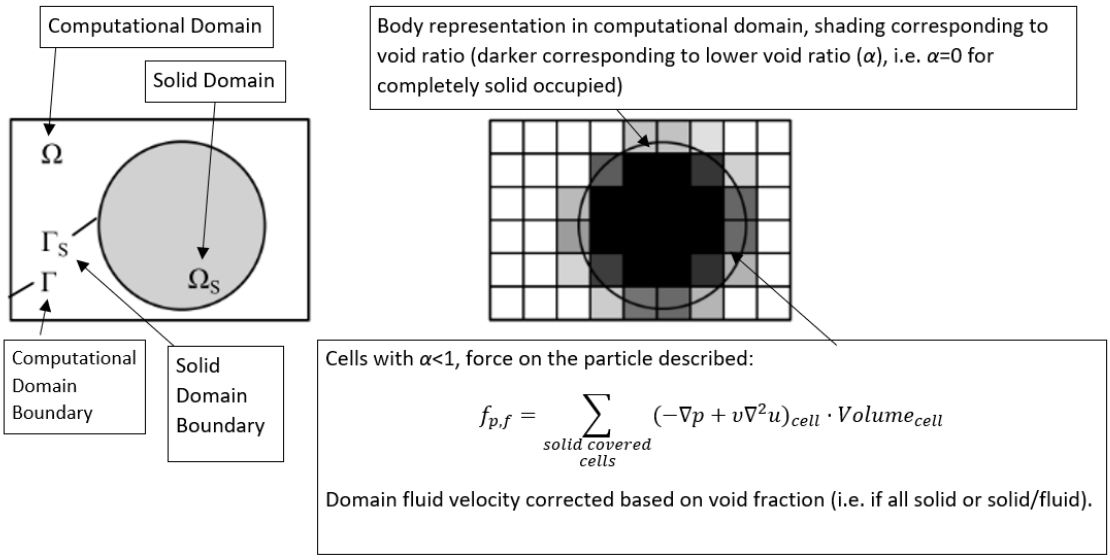


Figure 3: Schematic of particle-fluid coupling in resolved DEM-CFD method (as from [14,15]). $f_{p,f}$=fluid-particle force, p=pressure, υ=kinematic viscosity.

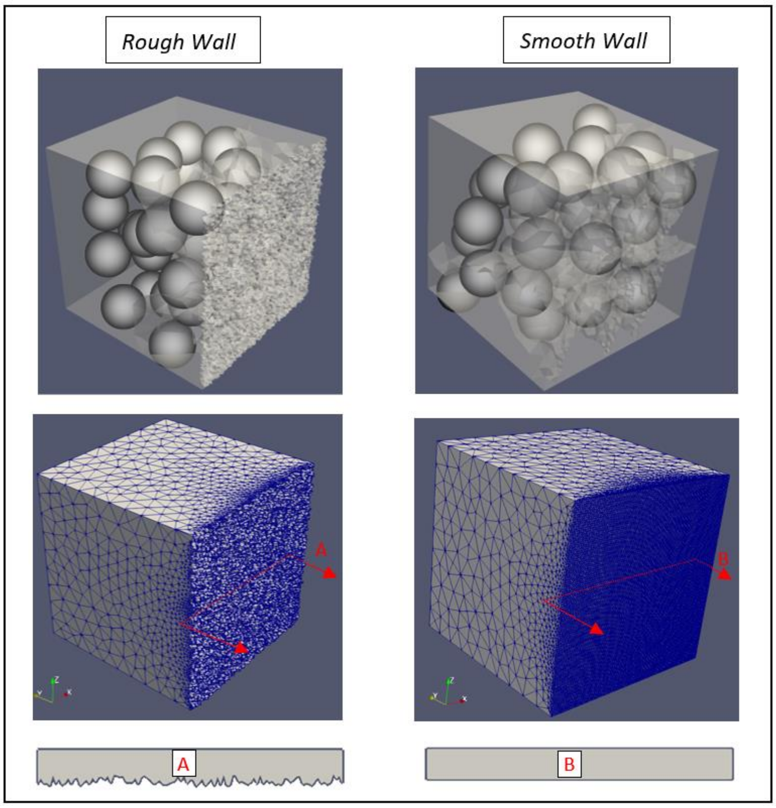
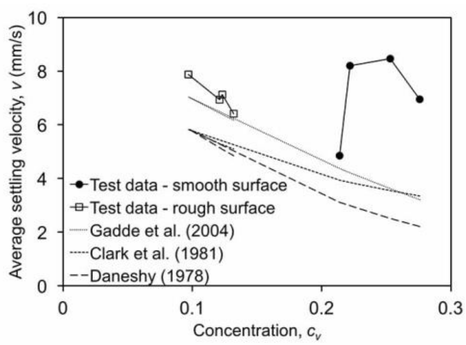
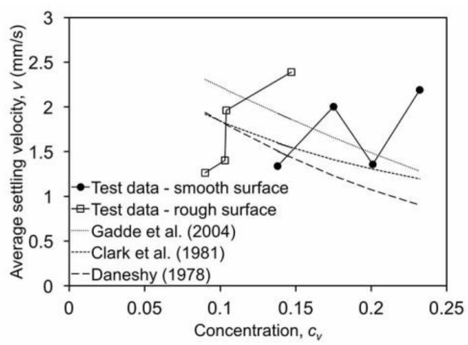


Figure 4: Initial model conditions (particle distribution and CFD mesh) for rough wall (fractal dimension = 2.454) and smooth wall (fractal dimension = 2.0) configurations. Both models with 39 randomly located particles in DEM domain (~31.9% initial volumetric concentration).



a)



b)

Figure 5: Comparison of particle settling between smooth and rough walls in different particle concentrations, a) fluid dynamic viscosity: μ=0.0355 Pa·s, fluid density: ρ=1198.45 kg/m^3 and b) μ=0.109 Pa·s, ρ=1221.8 kg/m^3 [11].

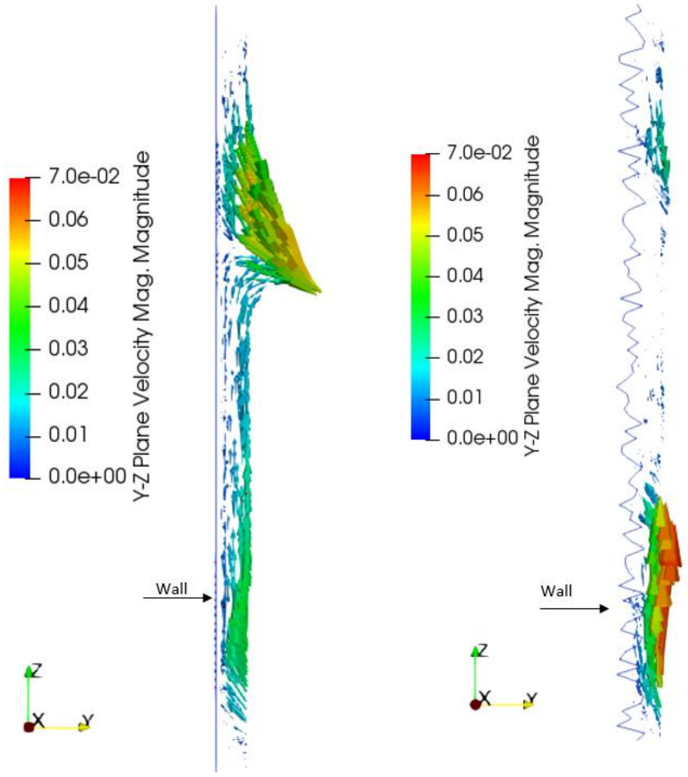


Figure 6: Near wall (0.04mm offset from wall) fluid cells' Y-Z planar velocity magnitudes (m/s) at mid-X domain slice sections (time = 0.23) sec for a) smooth wall and b) rough wall. Fluid velocities (and recirculation) dampened by rough wall.

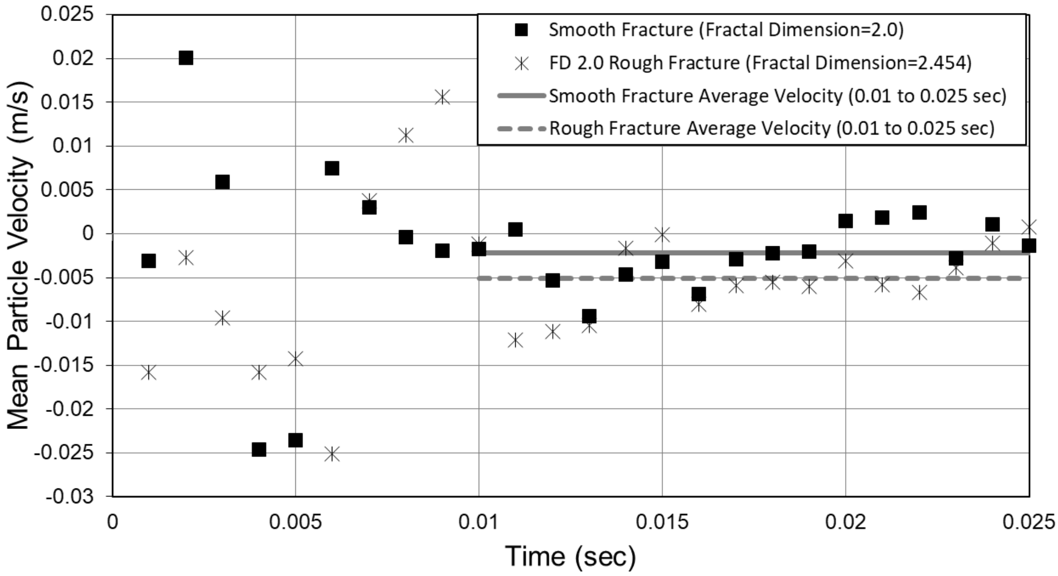


Figure 7: a) Mean particle Z-Velocity through simulation duration, with average Z-velocities from 0.01 to 0.025 sec.

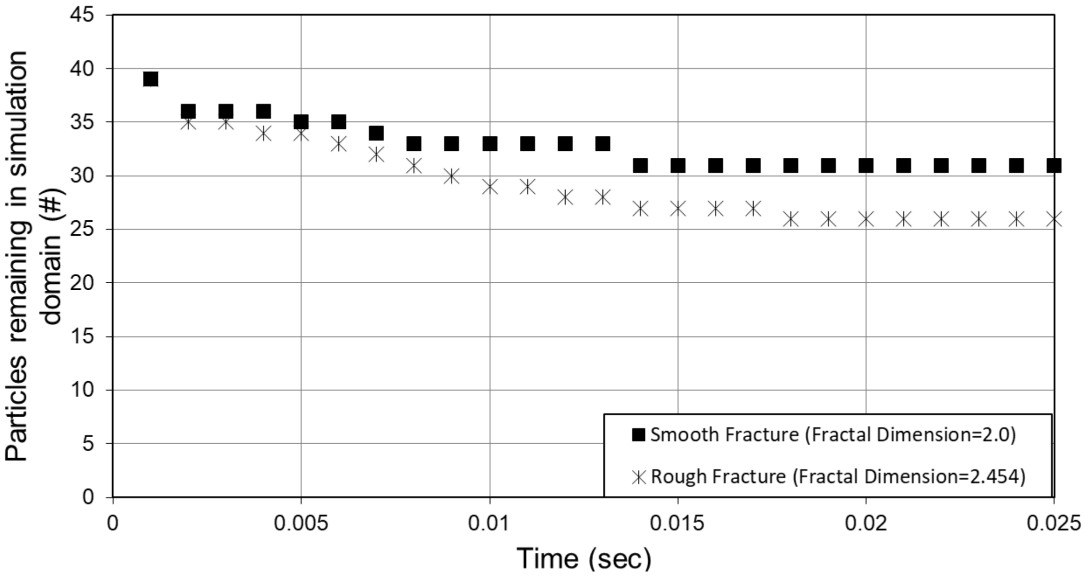


Figure 8: Particles remaining in simulation through simulation duration.

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