Numerical modeling of erosion in dense slurry flows

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ABSTRACT: Dense slurries are often produced and transported in mining engineering. Handling such high-volume fraction particulate flows often results in high pressure drop and severe erosion damage in facilities. Underestimating the erosion damage may result in catastrophic health, safety and environmental problems. The present study aims at modeling erosion in dense slurries by using computational fluid dynamics simulation. We use dense discrete particle model which takes into account both particle-fluid and particle-particle interactions. Numerical modeling is first conducted for a slurry impingement test with available experimental data through which the accuracy of the model is validated. Then, CFD simulation is conducted for a flow loop transmitting slurry flow. A comparison of the obtained CFD results with measured erosion rate (R^2=96.05%, mean percentage error=11.24%) indicates a great potential of DDPM for modeling erosion in dense slurries.

Keywords: Erosion, dense slurries, Numerical modeling, DDPM.

1 INTRODUCTION

Dense slurries are encountered in several industrial sectors such as mining and petroleum engineering. High volume fraction of particles in such flow systems results in several issues such as high pressure drop, particle deposition and erosion, to name a few. Fluid handling facilities in such systems suffer from severe wear and underestimating the damage from erosion may result in catastrophic health, safety and environmental problems. Hence, the capability of predicting erosion damage in a quantitative manner is of paramount importance for designing such systems.

Due to the importance of erosion in different industrial sectors, several studies were carried out to identify the influential factors affecting the severity of erosion. Besides, several models have been proposed to quantify the erosion damage (Arabnejad et al., 2015; Finnie, 1960; Oka et al., 2005; Zhang, 2006). Such erosion models are often used along with computational fluid dynamics (CFD) models to precisely predict the trajectory of particles and the erosion damage due to the interaction of particles and walls.

Thus far, several researchers used CFD models to investigate the flow-field and erosion in different geometrical conditions (Chen et al., 2006; Darihaki et al., 2017; Pouraria et al., 2017).

However, numerical modeling of erosion in dense slurries has been scarce. Furthermore, erosion prediction is often conducted using discrete particle model (DPM) in which the inter-particle collisions are totally neglected. Due to the low particle loading in most of processing systems such an assumption is generally valid. However, as the particle loading increases, the influence of suspended particles on the motion of carrier fluid and the inter-particle collisions becomes more important. In such cases, simplified models such as DPM cannot predict the flow fields. Hence, using more sophisticated methods are essential.

Discrete Element Method (DEM) is considered as the most appropriate alternative for predicting the flow-field in dense slurries that is capable of modelling inter-particle interactions. However, owing to the high computational cost, application of DEM is limited to the small-scale simulations. On the other hand, Eulerian-granular model, that is capable of considering inter-particle and fluid particle interactions, is not suitable for erosion prediction (Pouraria et al., 2020). In fact, due to the flux averaging in this method, the important information such as the particle impact velocity at the wall and angle of impact are not reliable, which in turn results in underestimation of the erosion.

Recently, application of hybrid CFD models such as dense discrete particle methods (DDPM) has drawn great attention (Pouraria et al., 2020). In such methods, individual particles are modeled using a Lagrangian approach enabling precise prediction of particle trajectories and particle-wall interaction. On the contrary, in the DDPM model interparticle collisions are modeled based on the kinetic theory of granular flows (KTGF) which is used in Eulerian-granular model. By employing the less demanding KTGF model for modeling inter-particle collisions and tracking groups of particles with similar motions, the computational cost in DDPM significantly reduces when compared to the DEM model. Hence, DDPM emerges as a suitable alternative model for predicting erosion in large industrial scale facilities where the application of DEM is not feasible.

The objective of the present study is to employ the DDPM model for predicting erosion in dense slurries. To this end, numerical model is employed to predict the erosion in standard slurry impingement test. A comparison of the predicted erosion using DDPM and experiment allows the assessment of the accuracy of the model. Furthermore, numerical simulation is conducted for dense slurry flows passing an elbow. Numerical modeling as obtained by the traditionally used DPM model and DDPM model are compared to see the influence of particle volume fraction on the erosion pattern.

2 NUMERICAL MODEL

In DDPM, the continuity and momentum equations are similar to the standard multi-fluid models:

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f\right) + \nabla \cdot \left(\alpha_f \rho_f \vec{v}_f\right) = 0$$

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f \vec{v}_f\right) + \nabla \cdot \left(\alpha_f \rho_f \vec{v}_f \vec{v}_f\right) = -\alpha_f \nabla p + \nabla \cdot \left[\alpha_f \mu_f \left(\nabla \vec{v}_f + \nabla \vec{v}_f^{\,T}\right)\right] + \alpha_f \rho_f \vec{g} + \vec{F}_{exchange} \tag{1}$$

where, α, ρ, v, and p indicate the volume fraction, density, velocity, and pressure, respectively. The subscript *f* denotes the fluid phase. In this approach, the conservation equations for the particulate phase are not solved (Pouraria et al., 2020). The velocity and volume fraction of particles are directly calculated based on the Lagrangian tracking of particles as follows:

$$m_s \frac{d\vec{u}_s}{dt} = m_s \frac{3C_d}{4} \frac{|\vec{u}_s - \vec{v}_f|}{d_s}\left(\vec{v}_f - \vec{u}_s\right) + m_s \frac{\vec{g}(\rho_s - \rho_f)}{\rho_s} + m_s \frac{\rho_f}{\rho_s} \vec{v}_f \nabla \vec{v}_f + \vec{F}_{KTGF} \tag{2}$$

In this equation, the first term on the right-hand side denotes the drag force exerted on the particle while the second and third terms show the buoyancy and pressure forces. The last term indicates the inter-particle collision forces that are calculated using KTGF model. Due to the importance of volume fraction in the present study, drag force was modelled using Gidapsow model.

The inter-particle collision is modelled base on the solid phase stress tensor $\bar{\bar{\tau}}_s$ (Syamlal et al., 1993):

$$\vec{F}_{KTGF} = -m_s \frac{1}{\rho_s} \nabla \bar{\bar{\tau}}_s \quad (3)$$

Turbulence was modelled by using standard k-ε model. Transient simulations were conducted by sufficiently small time steps to achieve convergence. Both flow-fields and Lagrangian particle tracking were modelled using identical time steps.

By employing this approach, the information required for erosion prediction is provided. In the present study, the ECR/C erosion model is employed to predict the thickness loss at the walls (Mansouri et al., 2015; Vieira et al., 2016).

$$\text{ER}=KF_s V_p^n f(\theta) \quad (4)$$

Where ER is the erosion ratio that is defined as the ratio of mass loss at the wall to the particle mass flow rate. Vp is the impact velocity of particles at the wall an n is a constant equal to 2.41. K is a constant that depends on the Brinell hardness of the pipe material and C is an empirical constant.

K is a constant that depends on the material of the pipe and is defined as follows (Mansouri et al., 2015; Vieira et al., 2016):

$$\text{K}= C(BH)^{-0.59} \quad (5)$$

$$\text{BH}= \frac{H_V+0.1023}{0.0108} \quad (6)$$

According to Mansouri et al. (2015), the appropriate value of K for slurry flow in stainless steel pipe is 1.15×10^{-8}. Furthermore, (θ) is the angle function that takes into account the influence of the angle of impact on erosion rate.

$$F(\theta) = \frac{1}{f}(sin\theta)^{n_1}(1 + {H_V}^{n_3}(1 - sin\theta))^{n_2} \quad (7)$$

Table 1 shows the employed constants for the stainless-steel material.

Table 1. Constants used in the angle functions.

Empirical constants	Values
$\boldsymbol{n_1}$	1.52
$\boldsymbol{n_2}$	8.9
$\boldsymbol{n_3}$	0.01
$\boldsymbol{H_V(GPa)}$	1.83
$\boldsymbol{f}$	18.74

3 RESULTS

CFD simulation was conducted for slurry impingement test with available experimental data. Figure 1 shows the schematic of the geometry in experiments conducted by Mahdavi et al. (2016). Water-sand flow with varying sand volume fractions were used in the test to investigate the influence of particle loading on erosion. The average velocity of slurry flow in the nozzle was 14 m/s. Sharp sands with the average diameter of $300\mu m$ were used in the experiments. Slurry jet is impacting a steel specimen that causes a sudden change in the direction of flow-field and severe particle impacts.

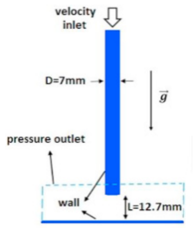

Figure 1. A schematic of the geometry and boundary conditions.

3D numerical modeling was conducted for the identical geometry and boundary conditions in the experiment. Figure 2 shows the contours of velocity of slurry as predicted by CFD model. Figure 3 shows the erosion ratio as measured in the experiments and predicted by the CFD model. As seen, both CFD data and experimental measurement indicate a considerable erosion reduction at high volume fractions. CFD data was generated for volume fractions as low as 1e-3 to better reveal the onset of erosion reduction. As seen in this figure, for volume fractions less than 5e-3 erosion ratio becomes independent of the volume fraction, which indicates that by increasing the particle volume fraction the erosion rate increases linearly. However, further increase in volume fraction of particles after a certain particle loading results in a comparatively less increase in erosion rate, thereby decreasing the erosion ratios. Figure 4 shows the profile of erosion at the steel specimen as predicted by the DDPM model. The depicted erosion profiles clearly show the erosion reduction as we increase the volume fraction. The erosion reduction phenomenon is attributed to the significant interparticle collisions near the wall where the collision among the incoming particles and rebounding particles becomes important. In fact, the collision of incoming particles with the bouncing particles results in a decrease in the impact velocity of particles. Furthermore, such collisions also result in higher dispersion of particles and changing their direction away from the walls.

CFD simulation was also conducted for a piping system transferring dense slurry flow. The experimental data of Yang et al. (2018) was used to validate the accuracy of the employed CFD model in the study.

Figure 5 shows the schematic view of the geometry in the experiment. A 3D CFD model was developed in Ansys-Fluent code. The pipe transfers mixture of water and sand and the average sand particle size in the experiment was $269\mu m$. Furthermore, a horizontal-vertical configuration was used to investigate the influence of particle deposition on the erosion rate. The velocity of slurry flow and sand volume fraction are 4.4 m/s and 8.6%, respectively. The lifetime of piping systems are generally determined by the erosion rate in the hot spots such as elbows and blinded-tees where a sudden change of flow direction happens. In the experiment, several sensors were used to quantify the erosion rate at elbow.

Figure 6 shows the predicted erosion rate for the elbow section as obtained by the CFD simulation. As seen, the maximum erosion rate is observed at the end of the elbow region and entrance of the vertical pipe. Table 2 shows a comparison of the predicted erosion rate using CFD and measurements

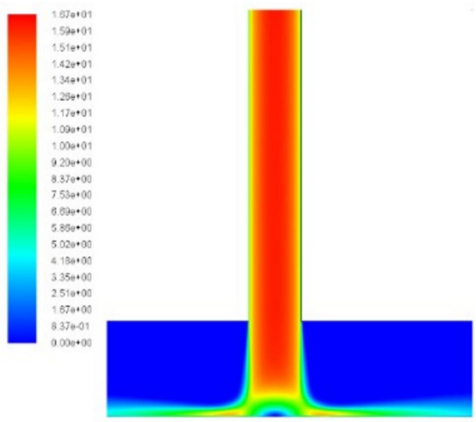

Figure 2. Velocity of fluid injected from the nozzle near the wall as predicted by CFD model.

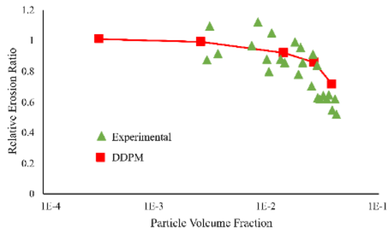

Figure 3. Erosion ratio as measured in the experiments and predicted by the CFD model.

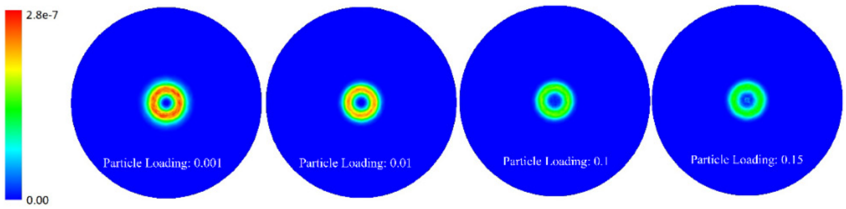

Figure 4. The profile of erosion at the steel specimen as predicted by the DDPM model.

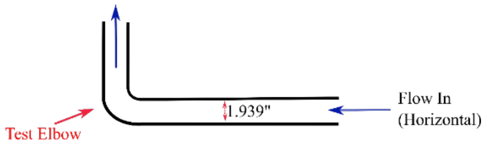

Figure 5. Schematic view of flow loop configuration for erosion test.

by sensors at different locations. The high value of R^2 and low value of the mean percentage error shows that there is a good agreement between the CFD predictions and the experimental measurements.

Figure 7 shows the distribution of particle volume fraction in the horizontal pipe and elbow section. As observed particle volume fraction at the top of the horizontal pipe section is the lowest and increases to the maximum value at the bottom. Using DPM for such cases usually results in predicting volume fractions greater than packing limit which is unphysical. However, by considering inter-particle collisions a reasonable distribution of volume fraction is predicted using DDPM.

The obtained results in this study indicate the great capability of DDPM in modeling dense slurries. The highest volume fraction in our simulations was 15% which is in accordance with the common volume fraction observed in oil-sands.

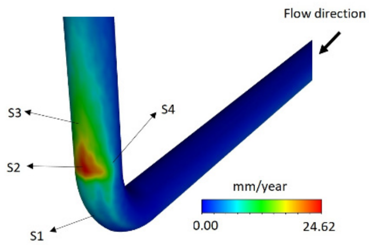

Figure 6. the predicted erosion rate for the elbow section as obtained by the CFD simulation.

Table 2. A comparison of the erosion rate predicted using CFD and experimental data.

Sensor	Experimental Data (mm/year)	Numerical Data (mm/year)	R^2	Mean Percentage Error
S1	6.1	7.2	96.05%	11.24%
S2	21.6	24.62		
S3	11.4	12.19		
S4	15	14.1		

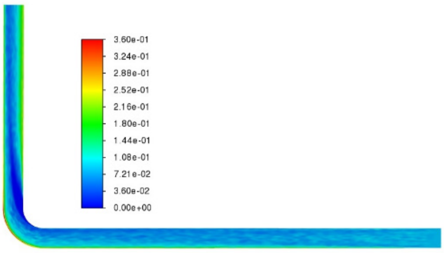

Figure 7. Distribution of particle volume fraction as predicted by DDPM.

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