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NUMERICAL PREDICTION OF THE IMPACT EROSION PRODUCED BY DENSE SLURRY JETS

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A new computational method is developed for reliable prediction of the impact erosion produced by dense submerged slurry jets. Predicting erosion of dense slurry flows is complex for a number of reasons, including the high computational cost of the two-phase flow models based on the Lagrangian tracking of the particles' trajectories, the lack of comprehensive models for particle-particle interactions and the lack of confidence in the validity of empirical erosion correlations. A possible frame of work for overcoming these flaws is proposed, consisting in the joint use of a computational approach developed by Messa and Malavasi (2018) for simulating efficiently the fluid dynamic characteristics of dense slurries in the proximity of an eroding wall, and of a strategy proposed by Mansouri et al. (2015a) for calibrating an empirical erosion correlation based on a limited set of numerical and experimental results. Validation against original experimental data confirmed that the combination of the two methods has the potential to be a reliable predictive tool for design purposes, thereby being worthy of consideration for further improvement.

KEY WORDS: Computational Fluid Dynamics, Slurry flows, Impact erosion.

1. INTRODUCTION AND OBJECTIVES

Solid particles entrained with the flow in hydro-transport systems are likely to produce serious erosion of pipes and pipeline components, enhancing the importance of disposing of reliable models for predicting the risk of wear. Additionally, growing capabilities of commercially available Computational Fluid Dynamics (CFD) codes are creating great opportunities for engineers to be able to compute the flow in even complex geometries. Based on these developments, the Erosion/Corrosion Research Center (E/CRC) of the University of Tulsa is regarded as a pioneer in establishing and promoting the use of CFD for predicting solid particle erosion (see, for instance, McLaury et al., 1994; Edwards et al., 1998). While, in the past, adding an erosion prediction post-processor to a commercially available CFD code required extensive user-defined programming (Forder et al., 1998; Edwards et al., 1998, 2001), nowadays utilities of this type are generally embedded in the latest releases, and they rely on a well-established two-step procedure. Firstly, the particle-laden flow is simulated by an Eulerian-Lagrangian (EL) model, in which the fluid flow equations are solved in an Eulerian framework, and the solid phase is simulated by tracking the trajectories of a certain number of computational particles (see,

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for instance, McLaury et al., 1994; Crowe et al., 2012). Afterwards, a "single-particle" erosion correlation is applied to quantify the mass of material removed by each particle-wall collision (Parsi et al., 2014). A widely used form of a single-particle erosion model is

$$E_\mathrm{p} = m_\mathrm{p} F_s K \left| \boldsymbol{v}_\mathrm{imp} \right|^n f\left(\theta_\mathrm{imp}\right) \tag{1}$$

where E_p is the mass of material removed by the particle-wall impingement, m_p is the particle mass, $|\boldsymbol{v}_\mathrm{imp}|$ is the modulus of the particle velocity vector at the stage of impingement, θ_imp is the angle generated by $\boldsymbol{v}_\mathrm{imp}$ and the wall at the stage of impingement, and F_s is a particle shape related parameter (Figures. 1a). K and n are numerical constants, which, together with the impact angle function $f(\theta_\mathrm{imp})$, are characteristic of the materials involved and their interactions, and are typically calibrated against laboratory experiments.

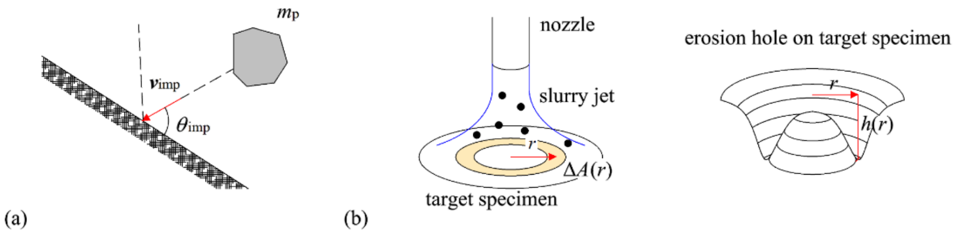

Figure 1. (a) an eroding particle hitting a surface (b) a slurry abrasive jet impingement test.

However, several aspects make the simulation of particle erosion a challenging task, especially for dense slurries. Firstly, EL models are computationally very expensive for slurry with large amounts of particles. Indeed, Eulerian-Eulerian (EE) models, providing a locally averaged representation of the two-phase flow field by modelling both phases in the Eulerian frame of reference (Crowe et al., 2012), are widely used for application to slurry pipelines, but their coupling with an erosion correlation is not straightforward, even if attempts in this direction have been reported in the literature (Mansouri et al, 2015b; Messa and Malavasi, 2018; Yu et al., 2019). Secondly, in the EL approach the solid particles are usually treated as point sources of momentum (point-particle approximation), often resulting in the inability to capture the effect of particle size on the wear behavior (Zhang et al, 2009). Thirdly, the CFD codes usually neglect the changes in the flow field caused by the eroding geometries, and this might affect the quality of the estimates depending on the time of exposure to erosion and the speed at which the damage occurs (Messa and Malavasi, 2018). Finally, possible sources of inaccuracy arise from the considerable number of uncertain sub-models and parameters of the CFD-based erosion prediction model, among which the erosion correlation plays a fundamental role (Messa and Malavasi, 2017). As already mentioned, most of these correlations are derived empirically and, since the calibration conditions are often partially or completely unknown, they are frequently misapplied, yielding results of doubtful validity. Indeed, the multi-scale approach by Leguizamon et al. (2017) introduced a different vision in the modeling of impact erosion through the modeling the damage produced by particle-wall impacts at the sub-particle scale by solving the laws of solid mechanics. Indeed, the search for physically based models should drive the efforts of researchers, but currently the computational cost of the multiscale approach seems incompatible with the engineering needs.

Recently, Messa and Malavasi (2018) proposed a computational method that addresses the first three limitations above, opening the way to the possibility of efficiently predicting the slurry erosion in the presence of high particle loading. Nevertheless, that strategy still suffered from the uncertainty inherent in the erosion correlation. In order to address this flaw, a technique formerly developed at the E/CRC to calibrate an empirical formula of the type as in Equation 1 based on a limited set of numerical and experimental data was explored. Slurry abrasive jet impingement experiments (Figure 1b) with solid mass fraction up to 15% performed at the E/CRC of the University of Tulsa were used for calibration and validation of the CFD results.

2. METHODOLOGY

2.1 CFD-BASED EROSION PREDICTION APPROACH

The approach employed for calculating the slurry flow field and predicting the erosion losses has been documented in Messa and Malavasi (2018). Owing to space limitations, only the key idea will be outlined hereafter.

The liquid-solid flow field is first calculated by means of an EE model developed by the authors for application to slurry pipelines, which yields the locally averaged fluid dynamic characteristics of the slurry, namely, the velocity vector of the liquid and solid phases, U_l and U_s, the two volume fractions, the pressure, and some turbulent properties of the liquid (Figure 2a). Close to the eroding wall, a thin, “Lagrangian” layer is defined, where the movement of the particles is represented in a Lagrangian framework (Figure 2b) through the tracking of Lagrangian particles injected from the boundary of the layer. The particle tracking is performed in steady-state mode, and the particles’ “initial” condition are deduced from the EE solution. When a particle reaches a distance from the wall equal to half of its size, an impact occurs, and an erosion correlation is employed to find the material removal caused by such impingement. In this way, the finite size of the particle is accounted for to avoid possible inaccuracies related with the already mentioned point-particle approximation. The sum over the impacts occurring in the same near-wall cells yields the displacement field of the near-wall nodes after a certain time interval, Δt (Figure 2c). The particle tracking is then repeated in a bigger domain, including both the Lagrangian layer and a “scar layer”, corresponding to the newly created erosion hole (Figure 2d). The erosion correlation is applied with the updated particle-wall impact characteristics and the calculation is iteratively repeated until the final time instant is reached. The dynamic procedure allows accounting for the influence of the eroding surface on the evolution of the erosion process. However, note that the EE simulation is executed only once in the domain with unchanged geometry, and, thus, no CFD data are available in scar layer. In order to calculate the particle trajectories, it was assumed that the fluid velocity was negligible compared to the particle velocity in the scar layer. Relying on a combination of EE modeling and Lagrangian tracking, the approach was referred to as “mixed EE/EL”.

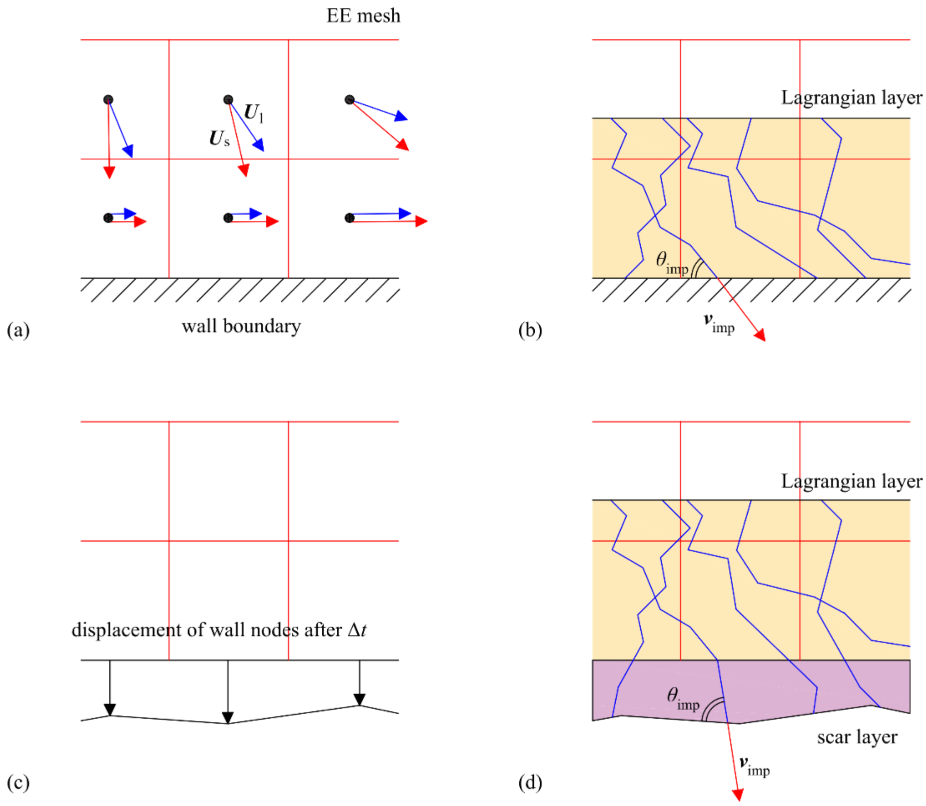

Figure 2. The computational approach for erosion prediction proposed by Messa and Malavasi (2018).

2.2 STRATEGY FOR EROSION MODEL CALIBRATION

A technique developed at the E/CRC at the University of Tulsa and described in Mansouri et al. (2015a) was used to calibrate the coefficients of an erosion correlation of the type as in Equation (1) by combining experimental measurements and CFD results of an abrasive jet impingement test in water. As for the mixed EE/EL approach, only the key idea of the calibration strategy is given. In an abrasive jet impingement test, a specimen of a target material is impinged at high velocity by a particle-laden jet for a certain time T, and the radial depth profile of the erosion hole, $h(r)$, can be experimentally determined with laser scanners or profilometers (Figures 1b and 3a). At the same time, the numerical simulation of the test provides the radial profiles of the locally averaged impact velocity,

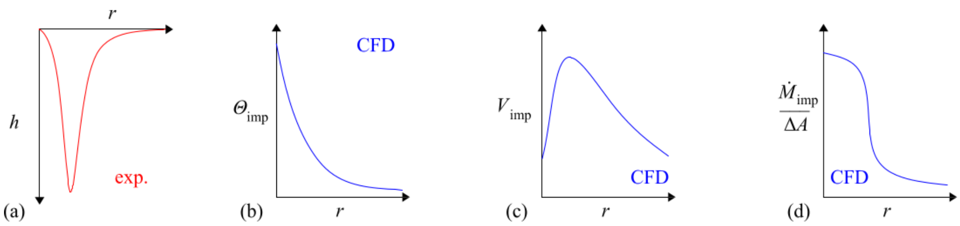

Figure 3. Schematic idea of the procedure of Mansouri et al. (2015a) to calibrate an erosion model from a slurry abrasive jet impingement test.

$V_{imp}(r)$, the locally averaged impact angle, Θ_{imp}, and the impinging solid mass flow rate per unit area, $\dot{M}_{imp}/\Delta A(r)$ (Figures 3b-d). In the above, V_{imp} and Θ_{imp} indicate the average of $|\boldsymbol{v}_{imp}|$ and θ_{imp} over ΔA, respectively, whereas $\dot{M}_{imp}$ is the total solid mass flow rate directed towards the wall over ΔA.

Mansouri et al. (2015a) proposed, first, to obtain the erosion depth profile by applying Eq. (1) at the "local area" (ΔA) level, and, then, to solve for $K{\cdot}f(\Theta_{imp})$, obtaining

$$K \cdot f\left(\Theta_{imp}\right) = \frac{h}{T \cdot F_s \cdot V_{imp}^n} \cdot \frac{\rho_w \Delta A}{\dot{M}_{imp}} \tag{2}$$

where ρ_w is the density of the target specimen. Calibration of the erosion model requires determining the proper values of n, F_s, K, and a suitable expression of the impact angle function, f. Mansouri et al. (2015a) assumed n=2.4, and they recommended F_s to be equal to 1.0, 0.53, and 0.2 for sharp, nearly rounded, and fully-rounded grains, respectively. Once these parameters have been established, the product $K{\cdot}f(\Theta_{imp})$ can be found by coupling the measured erosion depths with the calculated V_{imp}, Θ_{imp}, and $\dot{M}_{imp}/\Delta A$ profiles. The authors suggested fitting the combined numerical-experimental results on the following mathematical expression:

$$K \cdot f\left(\Theta_{imp}\right) = K \cdot \left(\sin\Theta_{imp}\right)^{b1} \cdot \left(1.5 - \sin\Theta_{imp}\right)^{b2} \tag{3}$$

thereby introducing two scalar variables b_1 and b_2 to represent the impact angle function. Note that the tuned parameters should be associated a confidence interval, accounting for the uncertainty of both the experimental data and the numerical fluid-dynamic results. At the moment, this is an unresolved task, recommended as topic for further improvement.

3. RESULTS AND DISCUSSION

Three abrasive slurry jet impingement tests performed at the E/CRC of the University of Tulsa were simulated using the PHOENICS 2014 commercial code and the in-house E-CODE developed within the FluidLab group at Politecnico di Milano. In all cases, the jet was directed perpendicularly to a 316 Stainless Steel specimen, whose density was estimated as 8000 kg/m^3, for a period of 30 minutes. The jet was completely submerged, and its velocity approximately 13.7 m/s. The working fluid was a mixture of water and sand particles with average size of approximately 300 µm, sharp corners, and density estimated as 2650 kg/m^3. The three tests differed by the solid mass fraction, C_m, which was 1%, 10%, and 15%, respectively. Although the erosion depth profiles reported in this study have never been published before, the reader can refer to Mahdavi et al. (2016) for a comprehensive description of the experimental setup and test procedure. In the same way, details about the numerical setup, including the 2D axisymmetric domain, the boundary conditions, the mesh and time settings, and the solution schemes, are given in Messa and Malavasi (2018).

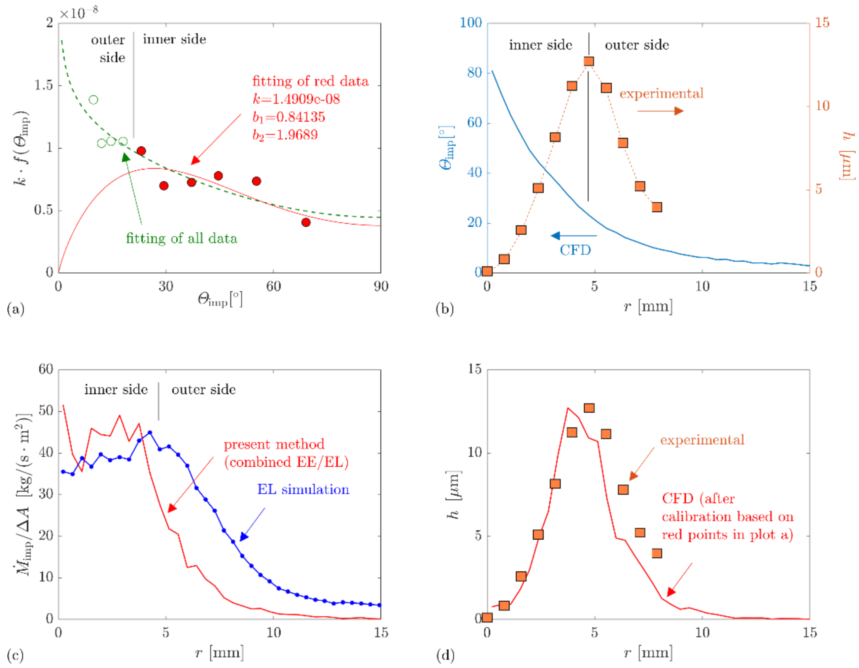

Figure 4. Results of calibration.

A two-step procedure was followed, consisting in the calibration of the erosion correlation for C_m=1% and the validation of the mixed EE/EL approach for C_m=10% and 15%. When C_m=1%, the maximum erosion depth was only about 12 µm, much lower than the particle size, thereby suggesting negligible effect of self-induced geometry changes. Therefore, no time loop was executed in the calibration phase. In Figures 4a, the computed values of Θ_{imp} are depicted versus the product $K{\cdot}f(\Theta_{imp})$, obtained from Equation 2 with n=2.4 and F_s=1.0. Fitting all points using an expression of the form of Equation 3 resulted in a monotonically decreasing impact angle function, which contradicts the well-established evidence that, for ductile materials, $f(\Theta_{imp})$ has a maximum at intermediate angles (Parsi et al., 2014).

In order to shed light on this unexpected finding, the erosion depth measurements were analyzed jointly with the corresponding Θ_{imp} predictions (Figure 4b), revealing that, in the outer side of the erosion hole, Θ_{imp} is lower than about 20°, and therefore, such outer part corresponds to the green unfilled points in Figure 4a. Figure 4c reveals that the mass flow rate intensity of impinging particles predicted by the mixed EE/EL method is almost constant and equal to about 45 kg/(s·m^2) in the inner side of the hole, and it suddenly drops to 0 in the outer side. Since the evaluation of $\dot{M}_{imp}/\Delta A$ was one of the most critical aspects in the mixed EE/EL approach, and it required several approximations and modelling assumptions, the profile of this variable was compared to that obtained by a full, one-way coupled EL simulation, in which the particles trajectories are calculated in the entire domain. As Figure 4c clearly shows, the mixed EE/EL method is likely to produce lower $\dot{M}_{imp}/\Delta A$ values in the outer part of the hole. When applying Equation 2, such underestimation of $\dot{M}_{imp}/\Delta A$ is necessarily compensated by artificially high $K{\cdot}f(\Theta_{imp})$, as indicated by the green points in Figure 4a. Understanding and overcoming this flaw of the mixed EE/EL approach is one of the research directions that the authors are currently pursuing. For the current study, it was decided to fit Equation 3 with respect to the inner side data only (red points in Figure 4a) to obtain a more reasonable impact angle function. Although, as expected, the erosion depth profile predicted using the calibrated model did not perfectly match the experimental in the outer side of the hole (Figure 4d), the overall trend is well captured and, therefore, the values n=2.4, F_s=1.0, k=1.4909e-08, b_1=0.84135, and b_2=1.9689 were employed to simulate the dense flow cases.

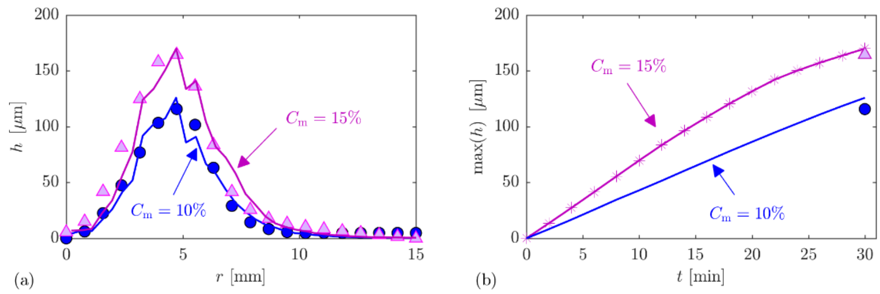

Figure 5. Results of validation phase: (a) erosion depth profiles at the end of the test (b) time evolution of the maximum erosion depth.

After calibration of the erosion model for the C_m=1% case, the mixed EE/EL approach allowed accurately predicting the erosion depth profile produced by the same type of abrasives at higher concentration (Figure 5a). Furthermore, the maximum computed erosion depth increases less than linearly in time (Figure 5b); in the mixed EE/EL approach, this trend arises from the combined effects of within- and between-phase interactions and self-induced geometry changes. The mixed EE/EL approach allows accounting for both effects without excessive computational cost, and therefore, it shows a new frame of work that can be implemented into CFD codes to develop a useful tool for engineering prediction of erosion in dense slurry flows.

4. CONCLUSIONS

The mixed EE/EL approach by Messa and Malavasi (2018) and the erosion model calibration technique by Mansouri et al. (2015a) were combined to predict the impact erosion produced by dense slurry jets. Calibration of the erosion correlation with respect to a single experiment at low concentration allowed obtaining accurate prediction of the damage produced by slurry jets with the same type of abrasives at higher concentration, which are harder to test in laboratory. Although the evaluation of the impinging solid mass flux was identified as a possible source of inaccuracy of the mixed EE/EL approach, which requires further improvement, the results confirmed that the proposed numerical framework could be a tool of considerable engineering interest.

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