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SIMPLIFIED COMPUTATIONAL APPROACH TO MULTI-PHASE EROSION

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ABSTRACT

Simulations of multi-phase erosion of protrusions in pipes are performed for instances of bubbly and slug flows, and compared with experimental observations. A methodology making use of a baseline slurry simulation coupled to post-processing filtering of the predicted erosion field achieves good accuracy while considerably simplifying and shortening the computations. In this methodology, experimental identifications of the flow regimes visited guide the post-processing filter definition to refine the predicted erosion distribution on the exposed surface of the target. The predictive abilities of this approach degrade for small particles due to effects caused by low particle Stokes numbers.

NOMENCLATURE

L	subscript, liquid phase
G	subscript, gas phase
V	velocity
d	particle diameter
nIPD	normalised Inter-Particle Distance

INTRODUCTION

Flow assurance is of critical importance in subsea oil and gas production systems, in part due to the instances of erosion from clastic (due to reservoir structure breakage) sand particles. Screening systems, well tubing, and pipes may all bear considerable erosion damage. Typically, an oil or gas well produces sand particles, liquids and gas. Sand is especially harmful in gas dominated operating conditions where the flow regime is of the slug or annular type. The exact erosion rate and distribution in the well are the result of complex multi-phase flow dynamics. Therefore, low-fidelity one-dimensional tools, based on correlations for ideal cases, are of limited accuracy in predicting erosion for a practical well configuration and it has been reported that the inconsistency of their prediction can reach two orders of magnitude (Salama 1998a). Use of such tools leads to bias in erosion prediction which has consequences on construction and maintenance costs. Solutions able to account for complex, representative geometries, operating conditions, and incorporating the interactions between the various materials at play in multi-phase flows are preferred.

Erosion is interpreted as the gouging or cracking of a massive target under the impact of hard particles, leading to removal of material (Finnie 1960). Erosion is primarily modelled in two-phase flows, that is, a single continuous fluid phase in which solid particles are tracked on the basis of the physics of drag and body forces. This approach is routinely used in industrial Computational Fluid Dynamics (CFD) as the Eulerian flow simulation and the tracking of Lagrangian parcels are established mature approaches (Zhang et al. 2007). Graham et al. (2009) demonstrate the method, where it is assumed that the slurry is only lightly loaded with particles. This assumption allows the erosion to be calculated as a post-processing step once the carrier flow field has been computed.

In contrast, erosion modelling in multi-phase configurations must be considered in its infancy and set-up and model simplifications vary greatly on a case-by-case basis. Bozzini et al. (2003) studied quaternary flows (liquid/liquid/gas/particles) in elbows with a homogeneous treatment of the multi-phase flow in which phases are assumed strongly coupled and share the same macro-scale fields. This approach precludes simulation where large voidage zones are present (slug flow, annular flow, etc.). In Huser and Kvernvold (1998), a multi-phase slurry flow was approximated as a single-phase slurry flow with representative density and transport properties for the mixture of liquids taken as the carrier of solid. The authors advocate that the discrepancies between CFD prediction and experimental data result from specific multi-phase effects on erosion not captured by such a simplified mixture model.

Rationale

The CFD techniques to predict multi-phase erosion do not perform well: (i) the number of physical models to enable such a simulation can be computationally expensive, and (ii) multi-phase CFD bears higher uncertainties than simpler single phase simulations. For this reason, it is worth investigating whether predictions of multi-phase erosion based on simple flow simulations perform within an acceptable level of accuracy, and also attempting to determine the conditions to achieve the full potential of this simplified approach.

Objective

This work proposes a simplified CFD approach to predict erosion on a target protruding in a multi-phase pipe flow experiencing slug or bubbly regimes. Emphasis is put on developing methodologies for conducting simulations of these difficult cases compatible with industrial business constraints. This configuration is representative, for instance, of erosion probes whose material loss must be monitored as an indicator of the severity of the erosion wear in the system (Salama, 1998b). Laboratory bench tests are used to assess the accuracy of the techniques developed.

Scope

This study is limited to erosion of a cross-flow cylinder by gas/slurry pipe flows in the slug and bubbly regimes. Given the simplifications underpinning the methodology, its extrapolation to significantly different configurations may not be warranted and would require further investigations.

Overview

The methodology developed is first explained, followed by the presentation of the experimental rig and cases investigated. Simulations and their results, compared with the experimental tests, are then introduced, showing a good agreement for this rapid and simple computational approach, except if erosion occurs in the low-Stokes number regime. A discussion section attempts an interpretation of these results, including the limits of the method for small particles.

METHOD

In pipes, gas-liquid flows exhibit a range of very specific dynamics, driven by their various superficial velocities: bubbly, annular, and slug/churn flows are highly transient. Capturing these multi-phase flows with CFD and supper-imposing Lagrangian tracking of sand particles to predict erosion is a difficult task, especially in practical geometries.

The method proposed in this contribution is based on drastic simplifications:

- the multi-phase flow is not modelled to the contrary of, for instance, Bozzini et al. (2003) or Huser and Kvernvold (1998) who rely on multi-phase mixture models. Sand particles are tracked on a single-phase flow whose fluid corresponds to the liquid phase.
- The impacts of the sand particles on the erosion target are processed by an erosion model that account for impact speed and angle and return the mass of removed material at the impact location.
- The predicted erosion rate is then, at the post-processing stage, weighted by an assumed time-average volume fraction of the liquid phase distribution as it passes the target (a simple multiplication on a point-by-point basis with the erosion field). Note that, from experimental observations in both the sludge and bubbly cases, the averaged distribution of the liquid volume fraction displayed a gradient due to the technique of gas injection in the rig and such distribution was included in the post-processing of the erosion rate assuming the gradient spun the range zero to unity. This was done fulfilling the requirement of total volume conservation for the slurry.

The underlying assumptions of this method are that the erosion process is essentially cumulative such that the transient sequences of the slurry impacting the target in a real multi-phase flow have virtually no effect on the overall erosion. The anticipated limits of these assumptions are the following:

- the distribution of the particles in the liquid volumes is not influenced by the morphing of the boundaries of the latter (gas/liquid interface). This is in fact a widely adopted assumption in the engineering of such flows since it is typically considered that particles keep being homogeneously distributed in the liquid volumes, whatever their shape.
- The trajectories of the particles inside the liquid volumes can be reasonably predicted while ignoring the fact these liquid volumes are driven by moving, transient boundaries. Particles are thus supposed carried by a slurry pipe flow whose bulk velocity is the mixture velocity of the real gas/slurry flow. Brutal events like splashing are not expected to be compatible with this assumption for fine particles which are known to adapt early their trajectory at the approach of an obstacle in an established steady-state flow.

Experiments are conducted to assess the value and limitations of the method.

Experiments

An experimental rig able to generate a range of pipe multi-phase flows between gas and slurry was designed and built. The rig consisted of a 'Y' junction where both gas and liquid phases meet, a long vertical section of approximately 40 pipe diameters to establish the flow regime, and a test sample upon which conveyed sand particles impacted. The test sample used in this work was a cross-flow cylinder presenting a 24% area obstruction. It was machined from Al6061-T6 aluminium. It was positioned centrally within a machined specimen holder during the erosion experiments and post-experiment was mounted on a Sheffield Discovery II D-8 Coordinate Measurement Machine (CMM) stage for surface profile measurements. The difference in the normal surface displacement relative to the uneroded surface determined the net loss of material after an erosion run. Surface measurements are accurate to within 2-3 μm in all axes of motion when a sample is securely mounted on the CMM.

The inlet of the Y junction that was in line with the downstream pipe carried sand-water slurry, while the side branch introduced air into the flow. The axis of the rig was oriented vertically upward. Superficial velocities of both gas and liquid phases were set to achieve the desired multi-phase flow regimes following maps established in the literature (Beggs and Brill, 1973), (Taitel et al., 1980). Details of the facilities, techniques and experimental protocols can be found in (Wong et al., 2014a), (Wong et al, 2014b).

Table 1 summarises the cases investigated with cases 1, 3F, and 10 aiming at achieving slug flows, and 2 and 11 bubbly flows.

Table 1: Experimental conditions and CFD runs performed.

Cases	1	2	3F	10	11
V_G [m/s]	19.28	4.67	32	20.5	4.51
V_L [m/s]	1.42	5.22	1.3	1.42	5.14
Sand [% ws/wl]	5.19	5.19	2.1	2.84	2.84
Sand [% vs/vl]	1.92	1.92	0.791	1.07	1.07
nIPD	3.73	3.73	5.02	4.54	4.54
Sand Density [kg/m^3]	2700	2700	2650	2650	2650
Sand Shape Factor	0.7	0.7	0.7	0.7	0.7
Sand d_{10} [μm]	175	175	106	1.32	1.32
Sand d_{50} [μm]	227	227	159	14.7	14.7
Sand d_{90} [μm]	311	311	240	49.4	49.4
Exposure Time [s]	3593	3600	881	3592	3639

Computations

The CFD analysis was performed using the package ANSYS-CFX and the ANSYS-CFD Suite for the pre- and post-processing stages, Version 14.5. Previous benchmarking and research demonstrated that these software are able to correctly predict erosion in binary flows with sand particles treated as Lagrangian parcels suspended in both water and air (Wong et al., 2013), (Solnordal and Wong, 2012), (Solnordal and Wong, 2011), (Wong et al., 2012), (Lester et al., 2010). Computations were performed using double precision.

Mesh

A composite mesh made of hexahedra, tetrahedra and prismatic regions was adopted to resolve the flow features and ensure numerical accuracy and efficiency. A fine, structured surface mesh existed around the cylinder sample for resolving the erosion distribution. The quality of the final mesh had a skewness below 0.5 and orthogonality larger than 0.5. The mesh independency was tested using the pressure drop and integrated skin friction across the rig as the assessed global variables through a three-level structured mesh refinement of average ratio 1.43. The Grid Convergence Index (Roache, 1994) was of the order of a few percent in the asymptotic range. The apparent order of convergence was 0.633. Discrepancies between the Richardson-extrapolated values and the three meshes were below 10%. The near-wall distance was constrained mostly in the ideal range ($y^+ \in [20{,}200]$) and the eddy-viscosity peaked at more than five nodes off any wall ensuring accurate flow feature resolution.

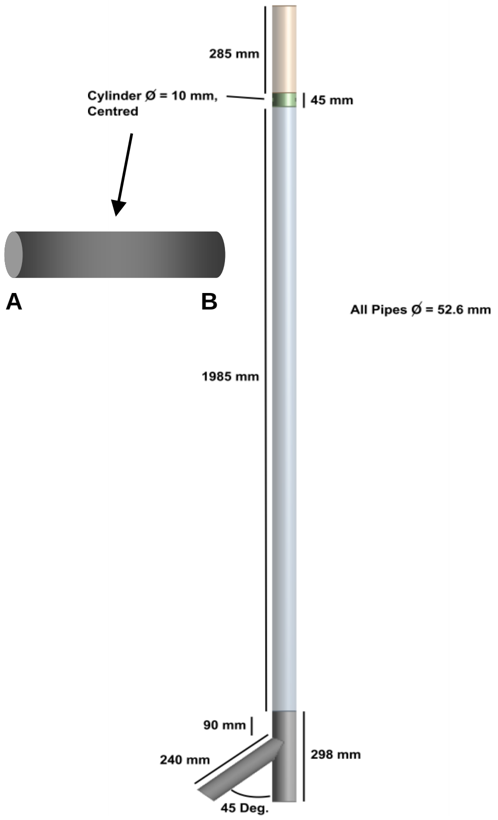

Figure 1: Dimensioned CAD representation of the experimental rig - elevation view.

Model Set-Up

Water, the carrier fluid of the sand, properties are chosen at normal conditions. The inlets were of a Dirichlet type with a "1/7" turbulent pipe flow profile for velocity (De Chant, 2005), a viscosity ratio of 10, and turbulence intensity of 5%. The turbulence model adopted was the *k-ω* SST model with curvature correction and automatic wall functions. Walls were numerically smooth with particles parallel restitution coefficients of 0.8 and perpendicular of 0.9. The outlet was of Neumann type. The CFX Pressure Coupled solver was employed with high order accuracy schemes for all variables.

The continuous phase is governed by the well known Navier-Stokes equations:

$$\frac{D\rho}{Dt} = 0 \tag{1}$$

$$\frac{D\rho\vec{U}}{Dt} = -\vec{\nabla}\mathrm{P} + \nabla \cdot (\tau + \tau_t) \tag{2}$$

where t is time, ρ is the fluid density, $\vec{U}$, its velocity, P the pressure, and τ the shear stress with the t sub-script indicating the turbulence shear stress.

The sand particles were tracked as statistical parcels by a Lagrangian solver on the converged water flow. Particles were subjected to turbulent dispersion, Schiller-Naumann drag, pressure gradient and virtual mass force. They were assumed to be spherical and poly-dispersed following the experimental size distribution and their injection covered the inlet boundary homogeneously and was made with zero slip velocity. As per Table 1 recalling the cases operating conditions, the normalised Inter-Particle Distance (*nIPD*) could drop below 5, which is considered as the limit before accounting for three- and four-way coupling. The Inter-Particle Distance is the radius of the sphere filling the largest region containing a single particle under the hypothesis of homogeneous distribution in the slurry. It is normalised by being divided by the particle radius. The representative particle size of the distributions was chosen as the median one for this *nIPD* calculation. Given the overall drastic simplification of the methodology proposed to predict the erosion of a cross-flow cylinder in instances of pipe gas-slurry flows, this issue was considered insignificant.

The parcel representing a homogeneous group of particles follows the equation:

$$m_p \frac{d\overrightarrow{U_P}}{dt} = \overrightarrow{F_D} + \overrightarrow{F_V} + \overrightarrow{F_P} \tag{3}$$

with m_p the particle mass, $\overrightarrow{U_P}$ its velocity, $\overrightarrow{F_D}$ the drag force, $\overrightarrow{F_V}$ the virtual mass force and $\overrightarrow{F_P}$ the pressure gradient force.

Flows were converged with RMS residuals at 10^{-5} for all variables. A convergence independency investigation showed negligible variations when the convergence was further tightened at 10^{-6}. Conservation relations, including for the discrete phase, were checked below 1%. Statistical as well as integration step independencies of the Lagrangian solver were assessed: 2 million parcels and 10 integration steps per element were found to be sufficient.

All the numerical quality tests mentioned here as well as in the previous Mesh Section were performed on Case 3F, considered as the most demanding because of the flow rate.

Erosion Model

The erosion model was from Wong et al. (2012). This is a semi-empirical model that accounts for the vectorial mass flow rate of the impacting stream. The generic shape of the model is derived from Chen et al. (2004) and parameters adjusted for the materials specifically involved: Garfield 70 sand, which is a semi-sharp type of sand, on aluminium T6-6061. Readers interested into the calibration protocol should consult these references. The final erosion model and its response, in particular, are discussed in (Wong et al., 2012).

RESULTS

In the following, water velocities and particle diameters are presented as non-dimensional groups for the sake of providing a quick snapshot of the flow and particle transport regimes. The velocity is presented as a Reynolds number based on the velocity value considered, carrier viscosity and cylinder diameter. The particle diameter is presented as a Stokes number based on the particle size considered, particle density, carrier viscosity, bulk velocity in the rig pipe, and cylinder diameter. The erosion rate is made non-dimensional using the mass flux density of dispersed material as imposed on the rig inlet cross section. Note also that extremities of the cylinder could not be mapped by the CMM, which explains a smaller length of the experimental erosion field compared to the CFD data.

Slug Flow Erosion Prediction on a Cross-Flow Cylinder

Figure 2 reports the streamlines and particle trajectories in the vicinity of the cylinder for Case 3F. Trajectories of relatively large diameter particles impact the cylinder but the low-Stokes particles are guided by the streamlines around the bluff body. Stokes numbers are high enough to make the wear process dominated by erosion and not abrasion, justifying the use of an erosion model coupled to Lagrangian parcel tracking.

Erosion prediction for Case 1 and 3F shows agreement with the experimental data in terms of general location and order of magnitude of the maximum erosion rate although the damage is more spread experimentally (Figure 3 and 4). Case 10, on the contrary, characterised by the use of fine sand, exhibits sparse impacts, precluding the reading of a statistically relevant value (Figure 5).

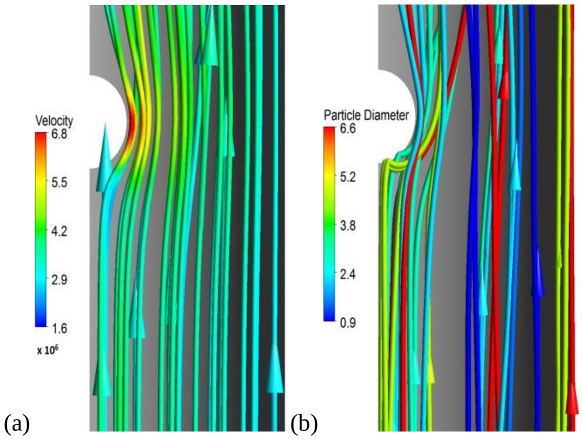

Figure 2: (a) Established streamlines, and (b) particle trajectories in the slurry flow at the Case 3F mixture velocity. Adimensional velocity and diameter.

Bubbly Flow Erosion Prediction on a Cross-Flow Cylinder

Erosion prediction for Case 2 is in overall agreement with the bench data as for the magnitude of the erosion damage (Figure 6) but is more localised. Case 11, characterised by the use of fine sand, exhibits sparse impacts which prevents the determination of a statistically relevant value (Figure 7).

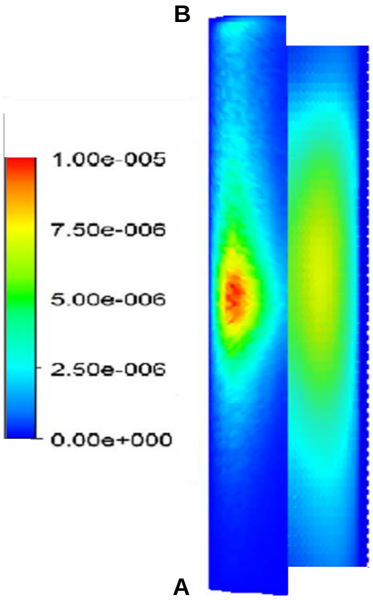

Figure 3: Erosion field [kg/kg], Case 1. Prediction (left) and experiments (right) adjacent following the cylinder symmetry plane. **A** and **B** sides are defined in Figure 1.

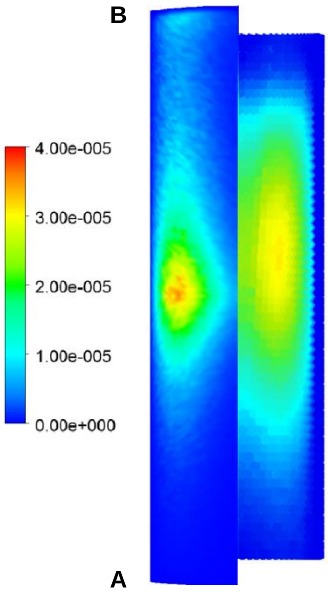

Figure 4: Erosion field [kg/kg], Case 3F. Prediction (left) and experiments (right) adjacent following the cylinder symmetry plane. **A** and **B** sides are defined in Figure 1.

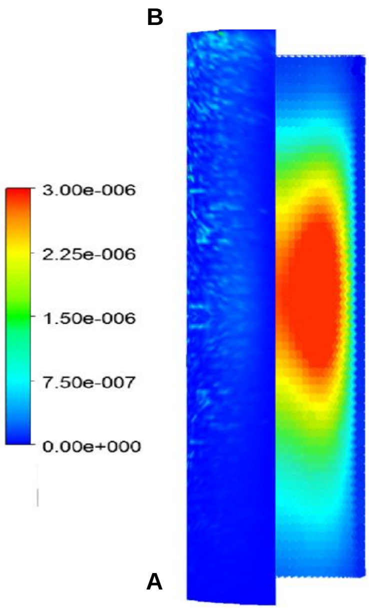

Figure 5: Erosion field [kg/kg], Case 10. Prediction (left) and experiments (right) adjacent following the cylinder symmetry plane. **A** and **B** sides are defined in Figure 1.

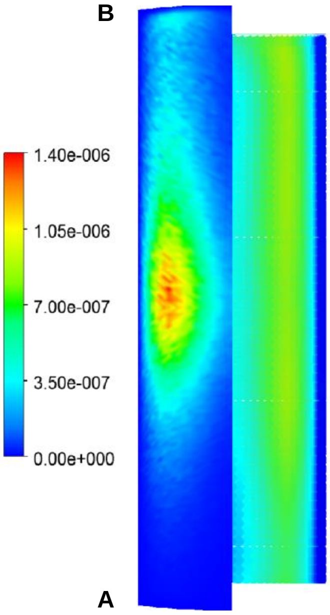

Figure 6: Erosion field [kg/kg], Case 2. Prediction (left) and experiments (right) adjacent following the cylinder symmetry plane. **A** and **B** sides are defined in Figure 1.

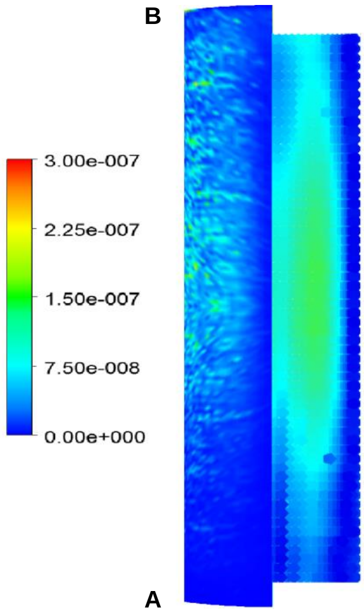

Figure 7: Erosion field [kg/kg], Case 11. Prediction (left) and experiments (right) adjacent following the cylinder symmetry plane. **A** and **B** sides are defined in Figure 1.

DISCUSSION

The key property underpinning the methodology is the cumulative characteristic of the erosion process. Considering that the erosion is only performed by the slurry and *a priori* determining the amount of slurry impacting the target from the knowledge of the multi-phase flow regime, steady-state slurry simulations at the gas-liquid mixture operating conditions can be post-processed to give erosion prediction of a good level of accuracy, considering the complexity of the case and the drastic simplifications employed. This can be observed for Cases 1, 2, and 3F (Figures 3, 6 and 4) in terms of maximum erosion rate, a quantity of integral engineering importance reported also in Table 2. Deviations of the prediction with respect to the bench data are lower than 100%, which is significantly better than the state-of-the-art of dedicated models (see above Introduction Section). Although it cannot rival with the degree of accuracy now possible for the CFD prediction of erosion in binary flow (particles carried by a single-phase fluid), it is a particularly good result in the context of multi-phase flow. In particular the order of magnitude of the maximum erosion damage is predicted, but the distribution of the erosion field is only approximate.

Table 2: Maximum erosion.

Case	Exp. [kg/kg]	CFD [kg/kg]	Error [%]
1	7.07×10^{-6}	9.04×10^{-6}	27.9
2	8.34×10^{-7}	1.21×10^{-6}	44.8
3F	3.12×10^{-5}	3.36×10^{-5}	7.7
10	3.62×10^{-6}	n/a	n/a
11	1.53×10^{-7}	n/a	n/a

The methodology provides interesting results as long as particles are not too small. Predicted erosion results for Cases 10 and 11, with significantly smaller sand, are not represented as no reading could be made for the erosion due to the scarcity of the particle impacts in the model under these conditions; this impact scarcity to be taken as a significant under-prediction of the erosion rate by the methodology proposed.

The fact that the proposed methodology based on slurry flow simulations followed by a specific post-processing does not lend itself to sand of small size is interpreted to be due to the strong drag of the liquid phase on the low-Stokes particles, such that these particles are constrained to follow the streamlines as they travel around the cylinder, Figure 2. In real two-phase flows of the slug or bubbly types, it is expected that the carrier streamlines do not settle as they do in pure slurry flows, so low-Stokes particles would in fact impact the target and contribute to erosion, as observed experimentally. The present methodology, relying on steady-state full slurry simulations, induces a bias against the low-Stokes particles by exaggerating the so-called "fluid effect" that directs small particles away from the target surface.

The artefact of a localised predicted erosion spot (whereas experimental erosion fields are more spread) can be traced back to the drastic simplification of using pure slurry simulations too. As the slurry flow establishes in the long pipe, its velocity profile morphs into the well known bell shape such that particles close to the centreline are carried at higher speed. Since erosion has approximately a squared response to the impact velocity, the centre of the target, in line with the fast-moving particles, is exposed significantly to more damages. Again, in real multi-phase flows the liquid may not organise in the same way.

CONCLUSION

- CFD of multiphase erosion is in its infancy. Given the huge variety and complexity of multi-phase flow physics, there is no fit-all model but rather several families of models whose selection must be performed with caution. Even so, if models are rightly selected, the state-of-the-art is such that the resolution of the flow is unlikely to have the same fidelity as less involved mono-phasic flows. Furthermore, some configurations develop multi-phase flow patterns whose resolution requires computational resources that are unreasonable in an industrial environment.
- This contribution has exposed a strategy to inexpensively solve slug and bubbly multi-phase erosion of a cross-flow cylinder in a straight pipe, which is a model problem for probes and other protrusions. The approach utilises the cumulative property of erosion damage to post-process

simple slurry flows in order to account for an *a priori* known gas-liquid regime in general terms.

- Following this method, erosion induced by bubbly and slug slurry flows has been inexpensively predicted with a level of accuracy that is significantly better than the state-of-the-art for multi-phase erosion.
- An important limitation of the simplified methodology relying on pure slurry simulations as presented here is that low-Stokes particles are carried by the streamlines of the established slurry flow and do not impact the target. It is believed that in multi-phase flows, streamlines are not organised the same way, allowing particles to contribute to the overall erosion of the target surface. Similarly, as the Stokes number effect magnitude is dependent on the geometry, the presented methodology may not work in configurations of different characteristics, at least for similar particles.

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