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A multiscale model for sediment impact erosion simulation using the finite volume particle method

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ABSTRACT

The erosion of a surface by a sediment-laden flow is an inherently multiscale phenomenon which includes physical interactions covering many orders of magnitude in both length and time scales. Conforming to the nature of the problem, we propose a novel multiscale model for simulating this complex process. On the one hand, a macroscale model encompassing the whole domain of interest solves the turbulent sediment transport problem. On the other hand, a microscale model simulates the sediment impacts against the surface. A sequential multiscale strategy is used to link the submodels, such that the microscale model provides closure to the macroscale model in terms of the calculated steady state erosion rate and restitution coefficients, therefore reproducing the original coupled problem. The proposed methodology is validated against experimental data for the slurry jet erosion of a copper plate at three impingement angles. Both the global erosion rate and the erosion depth profile are predicted with mean relative errors of 18% compared to the corresponding experimental values, achieving a significant improvement over correlation-based approaches.

1. Introduction

Hydroabrasive erosion is the gradual removal of material from a surface in contact with a sediment-laden flow [1]. Along with many other industrial components, hydraulic turbomachines experience hydroabrasive erosion which implies efficiency degradation, cavitation development, increased vibration and outage for expensive repairs [2,3]. This erosion damage can be mitigated by a combination of design, operation and maintenance measures, *e.g.* surface coatings, ad hoc turbine geometry, strategic shutdown in periods of high sediment concentration, periodic welding repairs, *etc.* [4]; any such measure yields some reduction in damage at a given economic cost. The ability to predict the erosion damage a turbine under specific conditions will experience would help reduce costs in the aforementioned decision making.

Hydroabrasive erosion consists of two phenomena: the erosion caused by the sediment impacts, and the abrasion occurring when the sediments are force to slide against the surface. The most important parameters in the case of sediment impact erosion are the impact angle and velocity. Other important factors include: the sediment material properties, size distribution, shape and concentration; the surface material properties, including microstructure; the fluid and flow characteristics such as density, viscosity and turbulence intensity [5]. Furthermore, these parameters are interdependent: for instance, the sediment size affects the energy content of any given impact, but it also determines the location, velocity and angle of the impact, for given fixed flow conditions.

The erosion phenomenon has been studied experimentally for half a century, providing important insight into the mechanisms driving it. Finnie [6–8] investigated the erosion of ductile and brittle materials and proposed analytical models to predict the amount of mass removed by any given impact. Bitter [9,10] proposed a different analytical model based on studies of two erosion mechanisms on ductile materials: the accumulation of plastic deformation, predominant at high impact angles, and the removal of material by cutting, effective at low impact angles. Both of these models are still used to date on a variety of empirical erosion correlations [5]. Shewmon [11] reports on the importance of strain rate and thermal effects, as well as the formation of lips and craters on the surface of the metal depending on the impact angle.

Numerical simulations have also been used to study the problem at hand; these efforts have followed two very different approaches. From the microscopic perspective, the details of sediment impacts have been studied with both finite element methods [12–14] and smoothed

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particle hydrodynamics (SPH) [15–17] using advanced constitutive modeling to capture the thermomechanical characteristics of this very high strain rate problem. The advantage of this approach is that the erosion is found by solving the governing equations of the material, rather than from an empirical correlation. Even though such material models also require some empirical input, such an approach is supported by broader physics and should therefore be more general. The inconvenience of this procedure is that it is limited to a microscopic scale, *i.e.* a domain size comparable to the sediment diameter, and simulation of a handful of impacts only. The second approach that has been taken by researchers focuses on the macroscopic phenomenon. Computational fluid dynamics (CFD) has been used to calculate the trajectories of sediments in impinging slurry jets [18–20] and hydraulic turbines [21] showing that the sediments impact the surface with a distribution of angles and velocities determined by the fluid dynamics and sediment properties. The advantage of this approach is that it allows for real world conditions: a distribution of sediment sizes, impact velocities and angles providing meaningful distributions of erosion over an extensive surface. The weakness of this procedure is that it disregards the material modeling, falling back on simple correlations to estimate the amount of material removed by each impact, implying a loss of generality. Indeed, it has been recently shown that deviations up to a factor of 5 are to be expected when using the best erosion correlation to predict the global erosion rate of an impinging slurry jet on a variety of configurations [22]; the other correlations show an even greater spread around the experimental data available.

Many engineering problems are characterized by multiscale phenomena in which small-scale processes induce large-scale effects. Although simplified approaches may model the problem by taking into account its large-scale characteristics alone, it is usually necessary to include the small-scale processes that are responsible for the large-scale dynamics in the first place, if accuracy is paramount. Multiscale models have been proposed for a variety of problems [23–28]. The idea behind any such model is to use the results of a detailed microscale model to improve the macroscopic model which describes the problem of interest.

The present investigation introduces a novel multiscale model for the sediment erosion problem. By simulating two independent scales, it is possible to combine the advantages of the aforementioned approaches: the detailed thermomechanical modeling of the surface required to predict the erosion on a general basis, as well as the scope necessary to capture the erosion distribution over an area of interest considering the transport of the sediments by the fluid. An appropriate interaction between these scales allows to reproduce the original coupled problem, rendering an otherwise intractable calculation possible.

It is common in literature to use the term particle to refer to the sediments causing the erosion. For the sake of clarity, in this paper only the term sediment is used; the term particle is employed to refer to the spherical volumes used to discretize the domain.

This paper is organized as follows: In Section 2 we present the mathematical models used, as well as the proposed multiscale methodology. Section 3 describes the validation of the model, followed by a discussion of the results in Section 4. We draw a short conclusion and present prospective developments in Section 5.

2. Modeling

2.1. Governing equations

Before describing the proposed multiscale model of erosion, we present all the submodels that are part of it.

The mass, linear momentum and energy conservation equations being solved are expressed as

$$\frac{d\rho}{dt} + \rho\nabla\cdot\boldsymbol{C} = 0 \tag{1}$$

$$\rho\frac{d\boldsymbol{C}}{dt} = \nabla\cdot(\boldsymbol{s} - p\boldsymbol{I}) + \boldsymbol{f} \tag{2}$$

$$\rho c_p\frac{\partial T}{\partial t} = \kappa\nabla^2 T + \dot{q} \tag{3}$$

where ρ is the density, $\boldsymbol{C}$ is the velocity, p is the pressure, T is the temperature, $\boldsymbol{s}$ is the deviatoric stress tensor, $\boldsymbol{I}$ is the identity tensor, $\boldsymbol{f}$ is the sum of volumetric and surface forces, $\dot{q}$ is the sum of heat sinks and sources, and $\frac{d}{dt}$ denotes the material derivative. Constant heat capacity c_p and thermal conductivity κ are assumed in Eq. (3) when dealing with the solid, whereas the fluid and the sediments are both assumed isothermal.

2.1.1. Fluid constitutive and turbulence models

The fluid is modeled as Newtonian and weakly compressible; its pressure is therefore obtained from an equation of state. The following form of the Tait equation is considered for water [29]

$$p = \frac{\rho_\circ a^2}{\gamma}\left(\left(\frac{\rho}{\rho_\circ}\right)^\gamma - 1\right) \tag{4}$$

where $\rho_\circ$ is the reference density, a is the numerical speed of sound and γ is set to 7. For a Newtonian fluid, using Boussinesq's eddy viscosity assumption, it follows that

$$\boldsymbol{s} = 2(\mu + \mu_t)\left(\dot{\boldsymbol{\varepsilon}} - \frac{1}{3}\mathrm{tr}(\dot{\boldsymbol{\varepsilon}})\boldsymbol{I}\right) - \frac{2}{3}\rho k\boldsymbol{I} \tag{5}$$

where μ is the dynamic viscosity, μ_t is the turbulence viscosity, k is the turbulence kinetic energy and $\dot{\boldsymbol{\varepsilon}}$ is the strain rate tensor, defined by the fluid velocity $\boldsymbol{C}_f$ as follows:

$$\dot{\boldsymbol{\varepsilon}} = \frac{1}{2}(\nabla\boldsymbol{C}_f + (\nabla\boldsymbol{C}_f)^T). \tag{6}$$

The standard $k - \epsilon$ turbulence model is used to calculate the turbulence viscosity, given by

$$\mu_t = \rho C_\mu\frac{k^2}{\epsilon}. \tag{7}$$

The equations for the turbulence kinetic energy, k, and its dissipation, ϵ, read

$$\frac{\partial(\rho k)}{\partial t} + \nabla\cdot\left(\rho k\boldsymbol{C}_f - \frac{\mu_t}{\sigma_k}\nabla k\right) = 2\mu_t(\dot{\boldsymbol{\varepsilon}}:\dot{\boldsymbol{\varepsilon}}) - \rho\epsilon \tag{8}$$

$$\frac{\partial(\rho\epsilon)}{\partial t} + \nabla\cdot\left(\rho\epsilon\boldsymbol{C}_f - \frac{\mu_t}{\sigma_\epsilon}\nabla\epsilon\right) = C_{1\epsilon}\frac{\epsilon}{k}2\mu_t(\dot{\boldsymbol{\varepsilon}}:\dot{\boldsymbol{\varepsilon}}) - C_{2\epsilon}\,\rho\frac{\epsilon^2}{k}. \tag{9}$$

The standard values of the model constants C_μ, σ_k, σ_ϵ, $C_{1\epsilon}$ and $C_{2\epsilon}$ are used [30]. We employ the standard wall function to account for the effect of the walls on the fluid. Although this approach is in general less accurate than resolving the boundary layer, it provides enough accuracy for the problem at hand. Indeed, negligible differences in the predicted global erosion rate and its distribution have been reported [22] among the $k - \epsilon$ model with standard wall function, its RNG variant with non-equilibrium wall function, and the $k - \omega$ SST which completely resolves the boundary layer.

2.1.2. Sediment turbulent transport model

The sediments are modeled as rigid; their mass and volume are constant, therefore Eq. (2) reduces to Newton's second law:

$$m\frac{d\boldsymbol{C}_s}{dt} = m\boldsymbol{g} + \boldsymbol{f}_h + \boldsymbol{f}_{c,w} + \boldsymbol{f}_{c,s} + \boldsymbol{f}_f \tag{10}$$

where m is the sediment mass and $\boldsymbol{C}_s$ its velocity. The hydrodynamic force $\boldsymbol{f}_h$ is explained further down. The sediment- solid wall contact force, $\boldsymbol{f}_{c,w}$, is calculated using a penalty method based on Hertz's contact theory, and is oriented according to the normal vector pointing from the solid wall particle towards the sediment particle. The sediment-