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Influence of particle turbulence model on a pipe elbow erosion prediction based on Euler-Euler approach

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Abstract

Multiphase flows in pipes are widely used in oil and gas industries to transport solid-liquid or gas-solid mixtures. Erosion caused by solid particles impact and friction becomes a major challenge for equipment maintenance and safety, especially at pipeline singularities such as elbows. In this work, a CFD study on wall erosion in a 90° standard elbow is performed using a multi-fluid approach, also called Euler/Euler, for poly-dispersed fluid-particle flows. A model is proposed for the erosion prediction by taking into account particle agitation obtained from the Euler-Euler approach. A good agreement with experiments is observed. Then, effect of different particle turbulence models on the erosion rate are investigated.

Introduction

Many previous works have been carried out by numerical simulations based on the Eulerian-Lagrangian approach to predict the erosion quantities, which is easy to couple with empirical erosion models requiring the instantaneous velocity of each particle at impact. However, the huge computational cost makes difficult to use this approach to treat high particle concentration or multiphase flows in realistic engineering configurations. Conversely, the Euler-Euler approach is ideal for these kinds of problems. Solid particles are modeled as a continuum in an Eulerian framework so only the mean dynamical properties of particles are provided such as the mean solid volume fraction and particle velocity. It exists only a few works that contribute to the erosion prediction by the Euler-Euler models (Messa et al. 2015). In the present work, a CFD study on wall erosion in a 90° standard pipe elbow is performed using the NEPTUNE_CFD code for poly-dispersed fluid-particle flows (Fede et al. 2016). A model is proposed to predict erosion rate based on an Euler-Euler approach.

Erosion model based on Euler-Euler approach

In order to compare with erosion depth measured in Solnordal et al. (2015), an erosion rate of mass ε_m is derived at first to describe the mass loss of target material per unit area per second ($kg_t/m^2/s$), which is related to the empirical erosion rate ε given by Ahlert (1994) and the particle flux towards the wall. Introducing the probability density function (pdf) $f(\mathbf{x}, \mathbf{c}_p; t)$ which is defined such as $f(\mathbf{x}, \mathbf{c}_p; t)d\mathbf{c}_p d\mathbf{x}$ is the mean probable number of particles with a centre of mass located in $[\mathbf{x}, \mathbf{x} + d\mathbf{x}]$ with a velocity in $[\mathbf{c}_p, \mathbf{c}_p + d\mathbf{c}_p]$, the

particle flux towards the wall per unit area \mathcal{F} ($kg_p/m^2/s$) can be express as

$$\mathcal{F} = \int_{\mathbf{c}_p \cdot \mathbf{n}_w < 0} m_p(\mathbf{c}_p \cdot \mathbf{n}_w) f(\mathbf{c}_p) d\mathbf{c}_p \quad (1)$$

where m_p is the mass of a single particle, \mathbf{n}_w is the unit normal vector pointing from the wall towards the flow.

Using Eq. (1) the erosion rate of mass ε_m can be written as

$$\varepsilon_m = - \int_{\mathbf{c}_p \cdot \mathbf{n}_w < 0} \varepsilon(\mathbf{c}_p) m_p(\mathbf{c}_p \cdot \mathbf{n}_w) f(\mathbf{c}_p) d\mathbf{c}_p \quad (2)$$

To calculate Eq. (2), several assumptions should be made. First of all, Eq. (2) is applied in each wall-boundary cell of the Euler/Euler simulation. Also we assume that the dynamical properties of particles are unchanged between the cell's centre and the real wall-impact position, namely when the particle-to-wall distance is one radius. Such an assumption allows to use the variables of wall-boundary cells for computing Eq. (2). Then, it is necessary to estimate the instantaneous particle velocity that is required in the empirical erosion rate model (in other words we have to prescribe the pdf shape). We assume firstly that the particle velocity distribution is Gaussian. Under these assumptions, the instantaneous particle velocity can be estimated by

$$c_{p,i} = U_{p,i} + \sqrt{\frac{2}{3} q_p^2} \cdot \hat{\xi} \quad (3)$$

where $U_{p,i}$ is the i^{th} component of the mean particle velocity and q_p^2 the particle turbulent kinetic energy (both are given by CFD). $\hat{\xi}$ is a random number following a normalized Gaussian distribution. It should be noted here, particle kinetic stress tensor may be strongly anisotropic in dilute

flows, especially in the near wall regions. The assumption $\overline{u_i'^2} \approx 2/3 q_p^2$ may overestimate the friction at the wall. To overcome this problem, the second order of particle turbulence model $R_{p,ij}$ is also used in the present study. Thus the instantaneous particle velocity can be evaluated by

$$c_{p,i} = U_{p,i} + \sqrt{R_{p,ii}} \cdot \hat{\xi} \quad (4)$$

the effect of this two different particle turbulence models on erosion rate is shown later.

To compute the erosion rate, the pdf is sampled over a given number, N_{samp} , of instantaneous particle velocities constructed with Eq. (3) or (4). Hence Eq. (2) is computed as

$$\varepsilon_m = -\rho_p \alpha_p \frac{1}{N_{samp}} \sum_{m=1}^{N_{samp}} \varepsilon^{(m)}(\mathbf{c}_p^{(m)} \cdot \mathbf{n}_w) \quad \text{if } \mathbf{c}_p^{(m)} \cdot \mathbf{n}_w < 0 \quad (5)$$

where $\mathbf{c}_p^{(m)}$ is generated with Eq. (3) or (4). In Eq. (5) we used the $n_p m_p = \rho_p \alpha_p$ and α_p is the mean solid volume fraction that is also given by CFD.

Results and Discussion

Experiment set-up and its erosion depth distribution on the pipe elbow surface are shown in Fig. 1. More details of the experiment are found in Solnordal et al. (2015).

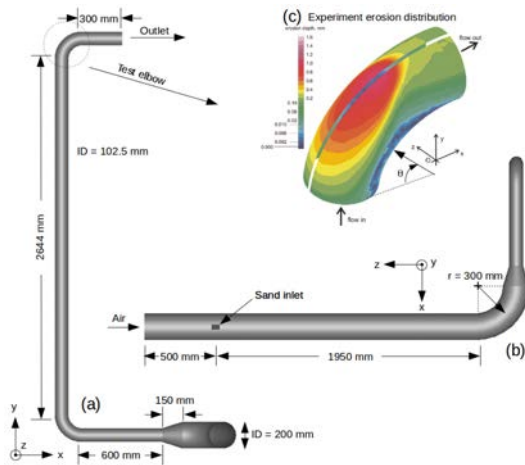


Figure 1: (a) and (b) Experiment set-up of Solnordal et al. (2015); (c) Contour of erosion depth after passage of 200 kg sand.

Results of the erosion model based on Euler-Euler approach are presented here. The erosion depth distribution with the particle turbulence model q_p^2 is shown in Fig. 2 (a). Compared to the experimental result in Fig. 1 (c), a very similar form is observed. The erosion depth profiles at the elbow extrados are presented in Fig. 2 (b) for two particle turbulence models. Result with the first order of turbulence model is in good agreement with experiment data, the maximum erosion depth is slightly overestimated. However, the erosion peak location is around 45° , which is 11° away from the experimental peak location 56° . It should be mentioned that the peak location predicted by other studies based on Euler-Lagrangian approach are also close to 45° . The discrepancy

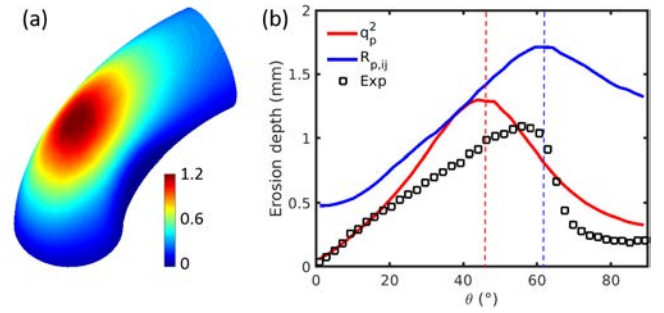


Figure 2: (a) Contour of erosion depth with the particle turbulence model q_p^2 ; (b) Erosion depth profiles on the elbow extrados for two different particle turbulence models, the dashed lines correspond to the erosion peak location.

on the peak location may suggest that it exists some additional physical mechanisms which are not considered in the modelings and simulations. It is also the motivation for using a second order of particle turbulence model that is more suitable to characterize the particle agitation in the near wall regions. As shown in Fig. 2 (b), profile of the second order of turbulence model predicts a much better peak location, even though the erosion depth is strongly overestimated, that is due to the free-slip particle boundary condition, compared to a roughness particle boundary condition for q_p^2 .

Conclusions

A CFD study on wall erosion in a 90° standard pipe elbow is performed using the NEPTUNE_CFD code. A model based on Euler-Euler approach is proposed and validated for erosion prediction. The consideration of anisotropy in the near wall regions by the second order of particle turbulence model helps to predict correctly the erosion peak location.

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