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Numerical simulation of solid particle erosion in pipe bends for liquid–solid flow

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ABSTRACT

Erosion caused by solid particles in pipe bends is one of the major concerns in the oil and gas industry which may result in equipment malfunction and even failure. In this work, a two-way coupled Eulerian–Lagrangian approach is employed to solve the liquid–solid flow in the pipe bend. Five different erosion models and two particle-wall rebound models are combined to predict the erosion rate. The most accurate model is chosen to calculate the effects of a range of parameters on erosion after comparing the predicted results with the experimental data. Further, the relationship between the Stokes number and the maximum erosion location is also assessed. It is found that although all these erosion models generate qualitatively similar erosion patterns, the Erosion/Corrosion Research Center (E/CRC) erosion model with the Grant and Tabakoff particle-wall rebound model produces results that are closest to the experimental data. Sequence of the influence of different parameters on erosion from the highest to the lowest is obtained: pipe diameter, inlet velocity, bending angle, particle mass flow, particle diameter, and Mean Curvature Radius/Pipe Diameter (R/D) ratio and bend orientation. Additionally, the relationship between Stokes number and the dynamic movement of the maximum erosion location is presented which can be used to predict the maximum erosion location for different operating conditions. Three collision mechanisms are proposed to explain how the changes of Stokes numbers influence the erosion location.

1. Introduction

Erosion caused by solid particles can be considered as a severe problem in the oil and gas industry. Sand is always entrained in the transporting fluid produced from the well. The small solid particles flow with the carried fluid and impact the inner wall of the piping, valves and some other components. The components face a high risk of solid particle erosion due to the constant collision, which may result in equipment malfunctioning and even failure [1–4]. As a complex process, erosion is affected by lots of factors. Particularly in the pipelines, small or subtle change of operating conditions can influence the damage due to erosion significantly. Obtaining accurate erosion regularities of different influencing factors is essential for predicting the service life of pipelines. Additionally, the accurate erosion prediction can also help in finding the spots where severe erosion is more likely to occur [2].

Many erosion models of solid particles are proposed to calculate the erosion rate of different components. Meng and Ludema [5] carried out a detailed investigation of the erosion models developed previously, and found 28 erosion models were related to solid particle impingement, as well as 33 key parameters that affect erosion rate. Several erosion models mentioned in their work are popularly used in predicting erosion rate for pipe bends, such as the models proposed by Finnie [6], Bitter [7,8], Neilson and Gilchrist [9], Grant and Tabakoff [10], and Hutchings [11]. The review indicated that each erosion model was developed based on a specific erosion mechanism and no single predictive equation could be used for practical erosion prediction. Since the 1990s, computational fluid dynamics (CFD) has been widely used for predicting erosion caused by solid particles. The CFD method greatly promotes the development of the erosion models and several widely used CFD-based erosion models are proposed [12,13]. Chen et al. [14] applied a CFD-based erosion prediction model that was developed by Ahlert [15] and McLaury [16] to predict the relative erosion severity between the elbow and the plugged tee with water/sand flow. The particle trajectories and the erosion pattern were analyzed by employing the Grant and Tabakoff [17] particle-wall rebound model. Wood and co-wokers [18] studied the particle distributions and particle impingement conditions in particle-laden liquids in horizontal-vertical (H–V) upward pipe bends. The Hashish [19] erosion model was implemented into the CFD software to study the effect of impact angles and impact velocities on the pipe. They found that erosion always occurred in specific areas. In another study [20], they performed their erosion research on small curvature bend and an upstream straight pipe section. The fluid phase was modeled using slurry flow. The in-plane wall erosion rate calculated by the Hashish erosion model [19] was in good

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agreement with their experimental data. Huang et al. [21] proposed a phenomenological erosion model based on their previous study [22] to calculate the erosion rate of material in slurry flow. The paper suggested that the erosion rate showed a strong dependence on the slurry mean velocity and a weak dependence on pipe diameter and fluid viscosity. The erosion rate has a power-law relation with particle diameter, slurry mean velocity, pipe diameter and liquid viscosity.

To investigate the effect of different factors on erosion of liquid–solid flow, various experimental methods have been adopted, such as the slurry pot test [23], jet impingement test [24], Coriolis erosion test [25] and pipe loop test [20,26–29]. The test methods except for the pipe loop test can only study the erosion of pipe materials and cannot be employed to evaluate the erosion of the real pipelines. However, the loop erosion tests of elbows with liquid–solid flow are much fewer than the other tests due to their huge consumption of time and great complexity of monitoring. Blanchard et al. [27] studied the effect of Mean Curvature Radius/Pipe Diameter (R/D) ratio and particle size on the pipe erosion by using the circulating loop system. They found that the value of the maximum erosion angle was almost the same for elbows under the conditions of different size particles or elbow properties. Wood et al. [20] used an experimental loop to explore the erosion rate of the straight and curved ducts. By comparing the results of three different test methods, they found that there was a remarkable increase for the erosion of the outermost side wall of the bends compared to the innermost side wall and significant erosion occurred at the base of the bend. Bourgoyne [28] measured the erosion rate of pipe bend with liquid–solid flow. He studied the effect of R/D ratio, particle mass flow rate and particle velocity on the erosion rate and obtained the maximum erosion angle. Although his experimental data of liquid–solid erosion is few, it was referenced by many investigators as a data base to develop erosion equations. Zeng et al. [29] investigated the erosion–corrosion (E–C) behavior of an X65 pipeline elbow by using the array electrodes technique. He studied the percentages of the pure erosion rate and found that most of the erosion occurred at the outermost side of the elbow.

Most of the currently available CFD-based erosion models and the experimental data of loop tests focus on the pipe bend with gas–solid flow. Studies on the erosion of the pipe bend with liquid–solid flow are relatively few and the accuracy of the erosion model in predicting the erosion of pipe with liquid–solid flow needs further validation. Since abrupt diversion will occur in the elbow section of the pipe which will lead to considerable difference in erosion, this work will look at particulate erosion of the elbow in more detail. The Eulerian–Lagrangian approach is used to solve the liquid–solid flow. The particle trajectory and the fluctuations of the liquid phase are simulated by the particle–eddy interaction method and the Discrete Radom Walk (DRW) model. Five erosion models and two particle-wall rebound models are combined to calculate the erosion rate. The particle–fluid interaction is accounted for by using two-way coupling. The erosion regularities of the pipe bends and elbows in different flow conditions are analyzed by using the most accurate erosion model. Furthermore, the relationship between Stokes number and the locations which are prone to erosion is also studied, and this relationship is explained by three different collision mechanisms.

2. Numerical modeling

The Eulerian–Lagrangian method is used in this study. The liquid is treated as a continuous phase and solved by the Navier–Stokes equations, while particles are treated as a discrete phase and solved by Newton's second law. Erosion modeling based on the CFD consists of three steps: the continuous phase flow field simulation, particle tracking, and erosion calculation. The first two steps will be described in this section and the last step will be described in the next section.

2.1. Liquid phase model

The Navier–Stokes equations are employed in this section. The continuity equations and momentum equations are written as:

$$\frac{\partial\rho}{\partial t}+\nabla\left(\rho\vec{u}\right)=0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho\vec{u}\right)+\nabla\cdot\left(\rho\vec{u}\,\vec{u}\right)=-\nabla P+\nabla\cdot\left(\bar{\bar{\tau}}\right)+\rho\vec{g}+\vec{S}_M \tag{2}$$

where ρ is the liquid density, $\vec{u}$ is the instantaneous velocity vector, P is the pressure, $\bar{\bar{\tau}}$ is the stress tensor, $\rho\vec{g}$ is the gravitational body force, $\vec{S}_M$ is the added momentum due to the solid phase.

The stress tensor is given by:

$$\bar{\bar{\tau}}=\mu\left[\left(\nabla\vec{u}+\nabla\vec{u}^{T}\right)-\frac{2}{3}\nabla\cdot\vec{u}I\right] \tag{3}$$

where μ is the molecular viscosity, I is the unit tensor.

The standard k-ε model is used to resolve the flow turbulence, and the equations are given as:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon+S_k \tag{4}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{5}$$

where G_k is the generation of turbulence kinetic energy due to the mean velocity gradients, $C_{1\varepsilon}$, $C_{2\varepsilon}$ are constants, u_i is the velocity component in i direction, x_i and x_j are the spatial coordinates, σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, S_k and S_ε are source terms, $\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$, $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $C_\mu=0.09$.

2.2. Disperse phase model

The particle trajectory is acquired by integrating the motion equation of the particles under the Lagrangian coordinates. While setting up the particle tracking and calculating the erosion rate, the following assumptions are made: (1) the injected particles are generally independent of each other and the reaction between particles is neglected, (2) the particle breakage is neglected, (3) the modifications of the elbow caused by the particles impaction are neglected. The governing equation of particle motion is proposed according to Newton's second law:

$$\frac{d\vec{u}_p}{\mathrm{dt}}=\vec{F}_D+\vec{F}_P+\vec{F}_{\mathrm{VM}}+\vec{F}_B \tag{9}$$

where $\vec{F}_D$, $\vec{F}_P$, $\vec{F}_{VM}$, and $\vec{F}_B$ represent the drag force, the pressure gradient force, added mass force and buoyancy force, the expressions of which are given as:

$$\vec{F}_D=\frac{3\mu}{4\rho_p d_p^2}C_D Re_s\left(\vec{u}-\vec{u}_p\right) \tag{10}$$

$$\vec{F}_P=\left(\frac{\rho}{\rho_p}\right)\nabla P \tag{11}$$

$$\vec{F}_{\mathrm{VM}}=\frac{1}{2}\frac{\rho}{\rho_p}\frac{d(\vec{u}-\vec{u_p})}{\mathrm{dt}} \tag{12}$$