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Numerical investigation of the erosion behavior in elbows of petroleum pipelines

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ABSTRACT

Oil spill caused by the erosion in elbows is widely encountered in long-distance crude oil transmission pipelines and will lead to a considerable economic loss and potential safety hazards. In order to prevent the equipment failure and evaluate the campaign life of piping systems, there exists an urgent need to identify the positions suffering severe erosion damage and predict the erosion rate in pipelines for multiphase flow. In this study, a mathematical model is established to predict the solid particle erosion in the elbows of petroleum pipelines, in which the particle-fluid interaction is taken into account. The effects of bend orientation and particle properties on the erosion process are investigated in details. In order to understand the erosion mechanism related with the dynamic behavior of flow fluid and entrained particles, the relationship between the secondary flows and the particle trajectories is analyzed emphatically. The results indicate that erosion mainly occurs in the regions near the elbow exit, especially the side walls of the downstream straight pipe and extrados of the bend section. However, erosion on the side walls could not always happen when the effect of the secondary flows is not remarkable. It is also found that the erosion behavior depends upon both the centrifugal effect of pipe flow and the forces acting on particles. Finally, an erosion pattern based on Stokes number is developed to quantify the complex coupled effects of the flow field and particle properties.

1. Introduction

Crude oil in long-distance transmission pipelines may entrain globs of water droplet, sand or dirt, which can coalesce and fall out of the oil flow in stretches of pipeline that run at lower pressure and temperature. Those deposited particles will cause erosion problems, which is attributed to the collisions between particles and the inner wall of the pipeline. Especially, they exacerbate the damage in elbows of pipelines due to the concerted effect of the pressure drop, centrifugal action and the dramatic change in flow field. As known, the serious erosion damage is a major threaten of the reliability and safety of piping systems, which will increase the equipment maintenance costs and environment burden resulting from potential spillage. Consequently, the accurate prediction of erosion behavior in elbows is of great significance to identify locations most prone to erosion and further evaluate the campaign life of long-distance crude oil transmission pipelines.

As well known, erosion severity is determined by a wide range of factors, such as production flow rate [1–3], multiphase flow regimes [4,5], fluid properties [1,3], particle properties [6,7], particle size distribution [8] and the equipment geometry [8,9]. And the changes in multiphase hydrodynamics have been recognized as the main reason for the variation of the erosion rate at different locations in any pipes. Therefore, many researchers tried to investigate the physics of erosion through the analysis of the fluid-solid two-phase flow system. Grant and Tabakoff [10] applied the Monte Carlo method to simulate the erosion in turbomachinery, taking account of the aerodynamic, rebound dynamics of particles as well as the material removal process. McLaury [11] proposed a generalized erosion prediction procedure covering three steps: flow simulation, particle tracking and erosion prediction, which have been the major procedure of many erosion models. Markus Varga et al. [12] developed a CFD-DEM-based erosion prediction model in feed pipes. In their study, a Computational Fluid Dynamics (CFD) approach was used to model fluid flow while a discrete element method (DEM) was adopted to describe the particle trajectories. As concluded by Yu and Xu [13], the CFD-DEM coupling scheme is attractive because of its superior computational convenience and higher capability to capture the particle physics. Mazumder [14] combined Eulerian CFD modeling with Lagrangian particle tracking to study the effect of liquid and gas velocities on the magnitude and location of maximum erosion in U-Bend. And the discrete phase model (DPM) was applied to simulate the particle motion in their work. DPM can use one computational particle in place of the particles with the same properties in a parcel. This will lead to a larger time step and smaller amount of stored information

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in DPM for a faster calculation and less computer resource. However, DPM is only appropriate for simulation of dilute particle flow, while the DEM method can be used for modeling of a broad range of flow regimes from low to high particle concentrations. In addition, a lot of modifications have been developed to improve the accuracy of particle tracks. Chen et al. [15] added a stochastic rebound model [10] to give a reasonable estimate about erosion rate and pattern. Zhang et al. [16] improved the particle near-wall velocity and erosion prediction through two modifications: applying standard wall function in the near-wall particle tracking and rebounding the particle at a radius from the wall, which can avoid nonphysical impacts.

Furthermore, since a multitude of factors have complex coupled effects on the erosion behavior, it is essential to clearly reveal the effects of different factors. Jafari et al. [17] investigated the effects of wall roughness on the erosion rate of gas-solid flow in horizontal annular pipes. The results showed that the erosion rates at both inner and outer walls would increase with the wall roughness. Chen et al. [18] studied the relative erosion severity between plugged tees and elbows. They found that the erosion severity was greatly influenced by the geometry of equipment and the carrier fluid (liquid or gas) properties. Burnett [19] suggested that the bend geometry could remarkably affect the puncture location, without presenting any details about the effect of different bend orientations. Deng et al. [20] carried out the experiments with four bend orientations and confirmed that the puncture point was indeed significantly affected by the bend orientation due to the biased particle distribution. Wang and Shirazi [21] conducted their research on the erosion of 90° elbows. They proposed that the squeeze film, secondary flows and turbulent flow fluctuations played important roles in erosion prediction when the carrier fluid was a liquid.

In general, erosion under multiphase flow is a very complex process and can be categorized into two parts: particle-fluid two-phase flow, and interactions between impacting particles and pipe wall. For the former, major interests lie in the particle distribution and particle trajectory which are strongly influenced by the flow field characteristics (e.g., secondary flows). Nevertheless, it is rarely concerned how the secondary flows affects the particle distribution and particle trajectory. The latter part is strongly associated with the particle impact dynamic information, such as impact velocity, angle, location and frequency. Unfortunately, all these information is rarely presented in the relevant literatures. Additionally, regarding to the effects of various factors (e.g., flow parameters, particle properties) on the maximum erosive location, previous researches were mainly focused on each individual factor, without the consideration of the coupled effects of different factors. In a word, few researches have made a comprehensive analysis of the erosion mechanism with the integration of flow field, particle motion, particle-fluid interaction and especially the impact characteristics of particle-wall. In this paper, an Eulerian-Lagrangian approach coupled with an available erosion model is employed to investigate the erosion mechanism of the liquid-solid two-phase flow in elbows. In order to reveal the erosion mechanism in terms of the particle-fluid interaction behavior and the particle-wall impact characteristics, the relationship between the secondary flows and the particle trajectories is investigated emphatically, and the particle impact information at the entire elbow is also depicted. In addition, the effects of particle properties and elbow orientation on the maximum erosive location are also discussed. Finally, an erosion pattern based on Stokes number is developed to quantify the complex coupled effects of flow parameters and particle properties.

2. Mathematical model

In this paper, three mathematical models are employed to study the erosion problems: flow field modeling, particle tracking and erosion prediction. The fluid is treated as a continuous phase and solved by the Reynolds averaged Navier-Stokes (RANS) equations in Eulerian scheme, while particles are treated as a discrete phase and captured by discrete phase model (DPM) in a Lagrangian framework. Further, the interaction between the continuous phase and the discrete phase is solved by the particle-fluid two-way coupling. In the coupled approach, when a particle trajectory is calculated, we keep track of the momentum variation of the particle stream that follows the trajectory, and then apply it into the subsequent calculations of the continuous phase flow field as a momentum source in the continuous phase momentum conservation equation. This two-way coupling is accomplished by alternately solving the continuous and discrete phase equations until a converged solution is achieved, in which both the continuous phase flow field and the particle trajectories are unchanged with each additional calculation.

To resolve particle-wall collisions and perform erosion prediction, additional sub-models are implemented into the CFD-based procedure. These sub-models consist of particle-wall collision rebound model and erosion model. As particles impact the wall at any time and any location, the impact information (i.e., impact frequency, speed, angle and location) are gathered using the particle-wall collision rebound model. And then the impact data can be applied to the erosion model, which will be related to the corresponding erosion rate in elbows.

2.1. Flow field modeling

For the fully developed, incompressible pipe flows, the flow field modeling is based on the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations. The time-varying conservation equations of mass and momentum equations are shown as below.

$$\nabla \cdot \left(\rho \vec{v}\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + \nabla \cdot \left(\rho \vec{v}\vec{v}\right) = -\nabla p + \nabla \cdot \left[\mu\left(\nabla \vec{v} + \nabla \vec{v}^{T}\right)\right] + \rho \vec{g} + S_{mom} \tag{2}$$

Here, ρ is the fluid density, v is the superficial velocity of the fluid, p is the pressure of the fluid, μ is the dynamic viscosity of the fluid, S_{mom} is the momentum transfer term between the continuous phase and the solid phase and can be computed as follows:

$$S_{mom} = \frac{-\sum\left(\overrightarrow{F_D} + \overrightarrow{F_B} + \overrightarrow{F_P} + \overrightarrow{F_{VM}}\right)}{V_{cell}} \tag{3}$$

where $\overrightarrow{F_D}$, $\overrightarrow{F_B}$, $\overrightarrow{F_P}$ and $\overrightarrow{F_{VM}}$ represent the drag force, buoyancy force, pressure gradient force and added mass force, respectively; V_{cell} is the volume of the CFD cell. In addition, to simulate the turbulent characteristics, the standard k-ε two-equation model is adopted. And the flow in the near-wall region is modelled by the standard wall function approach.

2.2. Particle tracking

In this part, the Lagrangian approach is applied into the particle tracking. The discrete phase model (DPM) is used to solve the motion equation for the discrete phase in a Lagrangian coordinates. In DPM simulation, the DPM concept of "parcels" is used to simulate the particle motion in the elbows. Namely, the particles with the same parameters and properties in the DPM parcel are represented by one computational particle. The calculated properties of the computational particles are used to describe the properties of the particle cluster.

The motion of an individual particle is determined by Newton's equation of motion. The forces acting on the particle in fluid are the gravity, drag force, virtual mass force, pressure gradient force, Magnus

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