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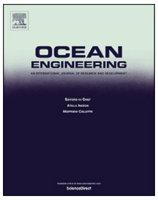

Numerical simulation of ice particle erosion in seawater pipelines of polar ship under vibration conditions

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ABSTRACT

Erosion in seawater pipeline caused by ice particles is one of the major concerns in the field of polar shipbuilding. The Eulerian-Lagrangian approach, dynamic grid technology, and erosion model are employed for simulating the erosion in vibrating pipeline. In this study, the vibration amplitudes of 1 mm and 2 mm and the vibration frequencies of 10 Hz, 20 Hz, 40 Hz, and 80 Hz are chosen. The results show that the vibration has a great impact on the erosion of seawater pipeline. Without vibration, the most serious erosion appears in the top of the pipe bend. With vibration of 2 mm and 80 Hz, the most serious erosion distributes as lines in the inlet and outlet straight sections. The maximum erosion rate of the pipe wall increases from 1.87×10^{-6} kg/(m^2·s) without vibration to 3.20×10^{-5} kg/(m^2·s) with vibration of 2 mm and 80 Hz, which almost increases by 17 times. The predicted service life of seawater pipeline reduces from 218.6 days without vibration to 12.8 days with vibration of 2 mm and 80 Hz. This study will provide references for the structural optimization design and erosion prevention of seawater pipeline of polar ship.

1. Introduction

With the opening of the Arctic channel, the key technology of polar shipbuilding has become a hot spot in the global shipbuilding industry. The Arctic channel has the advantages of shortening course, saving transit time, and reducing emissions and fuel consumption relative to the traditional commercial routes such as the Suez Canal and the Panama Canal. However, when the Arctic sea ice melts in summer, a large number of small ice particles are inhaled into the seawater system of polar ship, forming seawater-ice two-phase flow, which is easy to cause erosion in seawater pipeline.

There are many researchers studying on the erosion of pipeline caused by liquid-solid two-phase flow. The studies mainly focus on two aspects: experimental test and computational fluid dynamics (CFD) simulation. To investigate the effect of different factors on the erosion caused by liquid-solid two-phase flow, various experimental methods have been adopted, such as jet impingement test (Mahdi et al., 2014), slurry pot test (Desale et al., 2005), Coriolis erosion test (Xie et al., 1999), and pipe loop test (Wood et al., 2004; Zeng et al., 2014). Blanchard et al. (1984) used a mitre bend, and bends with Mean Curvature Radius/Pipe Diameter (R/D) of 1.5 and 5 for testing the erosion caused by water-sand two-phase flow. The wear coefficient, wear position, and wear depth were studied. They found that the maximum erosion angle was almost the same under different size particles and elbow properties. Bourgoyne (1989) used a diverter system to study the effect of sand rate, velocity, fluid type, and fitting type on erosion rate of pipe wall, and then proposed the equations for estimating the erosion rate in diverter systems. Meng and Ludema (1995) found 33 key parameters affecting the erosion rate by conducting a detailed investigation of the previously developed erosion wear experiments. Wood et al. (2004) used a pipe loop test to explore the erosion rate of the straight and curved ducts. They found that the erosion of the outermost sidewall was more serious compared with the innermost wall, and the bottom of the bend was significantly eroded. Zhang et al. (2013) explored the correlation between the wall erosion and the hydrodynamics of fluid flow by designing a scouring experiment similar to a real pipe. Although experimental test is a good method to study the erosion of the pipeline, it costs much money and time. By the development of computer technology, the specific physical parameters and flow structure of fluid-solid two-phase flow can be numerically simulated based on CFD method (Njobuenwu and Fairweather, 2012; Parsi et al., 2014). CFD method is the current popular trend to study the pipeline corrosion and erosion, which is more convenient and

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economical than the experimental method. Chen et al. (2006) predicted the relative erosion severity between the elbow and the plugged tee with water-sand two-phase flow using an erosion model. Wang et al. (2014) studied the effect of Stokes number on the erosion rate of 90° elbow based on no change of fluid flow, particle diameter, and flow parameters, and found that high Stokes number inconspicuously arise erosion on the side walls of the downstream straight pipe close to the bend exit due to the inadequate effect of the secondary flow. Although the erosion of the pipeline caused by liquid-solid two-phase flow has been widely studied, there are few researches focusing on the erosion caused by seawater-ice two-phase flow.

Currently, the studies of pipeline erosion are mostly in the static case, but this is not consistent with the actual situation. During sailing, the ship normally has natural vibrations at frequencies less than 80 Hz as a result of the waves, mechanical operation, ice breaking, and fluid pulsation (Wang et al., 2007; Fukasawa, 2012). The effect of vibration on pipeline erosion cannot be neglected, because the vibration changes the movement of solid particles, resulting in more complicated pipe erosion. Although the pipe erosion caused by liquid-solid two-phase flow under vibration is important, little work has been done yet.

In this paper, we study the influence of ice particles on the erosion of 90° elbow pipe under different vibration conditions using the discrete particle model (DPM) and dynamic grid technology. The vibration amplitudes of 1 mm and 2 mm and the vibration frequencies of 10 Hz, 20 Hz, 40 Hz, and 80 Hz are chosen. The results can be used for the structural optimization of the seawater pipeline system of polar ship and for the prevention of pipe erosion during its polar navigation.

2. Mathematical models

The Eulerian-Lagrangian approach is chosen for the seawater-ice two-phase flow. The seawater is treated as a continuous phase and the ice is treated as a discrete phase. The erosion rate of pipe wall is calculated by the solid particle erosion models. Since the concentration of ice is low, the seawater-ice two-phase flow is regarded as an incompressible Newtonian fluid with turbulence characteristics. The governing equations are continuity equation, momentum conservation equation, and k-ε turbulence model.

2.1. Continuous phase control equations

The Navier–Stokes equations are used. The continuity equation and momentum equation are written as:

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

$$\frac{\partial}{\partial t}(\rho u)+\vec{\nabla}(\rho\vec{u}\rightarrow\vec{u})=-\nabla P+\nabla(\tau)+\rho\vec{g}+\vec{S}_M \tag{2}$$

where ρ is the seawater density, u is the velocity vector, P is the pressure, S_M is the momentum change, τ is the stress tensor which is given as:

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

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

2.2. Discrete phase control equations

In DPM, the Navier–Stokes equation is solved for the continuous phase in the Eulerian framework and the particle trajectory equation is solved for the discrete phase in the Lagrangian framework (Njobuenwu and Fairweather, 2012; Parsi et al., 2014; Shang et al., 2014; Zhang et al., 2016). The trajectory equation, heat transfer equation, and mass transfer equation of the solid particles can be solved by integrating the discrete time steps. Then the particle velocity on the particle trajectories in each position can be calculated (Njobuenwu and Fairweather, 2012; Parsi et al., 2014). The equations are as follows:

$$\frac{d\vec{u}_p}{dt}=F_D(\vec{u}-\vec{u}_p)+\vec{g}\frac{(\rho_p-\rho)}{\rho_p}+F_v \tag{4}$$

$$F_D=\frac{3\mu}{4\rho d_p^2}C_d\mathrm{Re}_s \tag{5}$$

$$F_v=\frac{1}{2}\frac{\rho}{\rho_p}\frac{d(\vec{u}-\overrightarrow{u_p})}{dt} \tag{6}$$

where u is the velocity of seawater, u_p is the ice particle velocity, ρ is the density of seawater, ρ_p is the density of ice particle, d_p is the ice particle diameter, μ is the viscosity of seawater, C_d is the drag coefficient, g is the gravitational acceleration, F_D is the drag force, F_v is the lift force, additional mass force, thermophoresis force, and Brown force.

2.3. Wall collision recovery equations

Ice particles rebound after impacting the wall, which has a great influence on the movement of the trajectory. The rebound coefficient equations can be used to show the whole collision process. The velocity of ice particles is decomposed into the normal velocity and the tangential velocity. The movement of a particle impacting the wall is shown in Fig. 1.

The normal and tangential coefficients are expressed as follows (Grant and Tabakoff, 1975):

$$\begin{cases}\varepsilon_N=\dfrac{u_{p2}}{u_{p1}}=0.993-1.76\theta+1.56\theta^2-0.49\theta^3\\ \varepsilon_T=\dfrac{v_{p2}}{v_{p1}}=0.988-1.66\theta+2.11\theta^2-0.67\theta^3\end{cases} \tag{7}$$

where T and N are the normal and tangential respectively, u_{p1} and u_{p2} are the normal velocity of the particle before and after impacting the wall respectively, v_{p1} and v_{p2} are the tangential velocity of the particle before and after impacting the wall respectively, θ is the impact angle.

2.4. Erosion model

There are many factors leading to particle erosion, such as particle characteristics, impact speed, impact angle, flow velocity, volume fraction, and the shape of pipe. Considering the fluid dynamic characteristics and the shape of the bend, we choose the ice particle erosion model from the literature (Grant and Tabakoff, 1975). This model has been applied to many other particles (Zhang et al., 2007; Wang et al., 2014), so we assume that it can be applied to ice particle as well. The model selected is

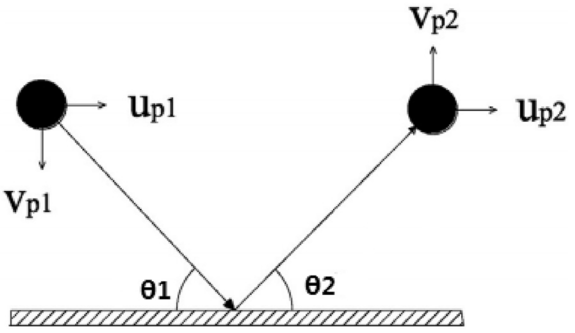

Fig. 1. Movement of a particle impacting the wall.