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Prediction of particle distribution and particle impact erosion in inclined cavities

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ABSTRACT

The cavity is one of the basic structures in pipe systems, but it is vulnerable in erosive environments. Cavities can occur in various places throughout industrial processes, each making a difference in the distribution of erosion. The aim of this study is to investigate gas (air)-solid flow properties and erosion characteristics in inclined cavities. A two-way URANS (SST)-DPM method was adopted. The simulations were carried out for three Stokes numbers (*St*), eight height differences (*h*) from 0 to 0.8*H*, and ten inclination angles from 0° to 90°. Results indicated that gas flow properties change little with inclination angle (φ). However, a variation in φ resulted in a change in the distribution of the particles and erosion on the aft wall, especially when *St* were 1.2 and 9.1. The particle number (*N*) in the zone 10 mm from the aft wall decreases linearly with φ for both previously mentioned *St*, and the slopes of *N*-φ curves increase exponentially with *h*. The maximum erosion rate (E_m) on the aft wall also decreases linearly with φ for the *St* of 1.2, and the negative slope of E_m-φ curve follows an exponentially increasing with *h*. But E_m decreases quadratically with φ when *St* is 9.1, and the function coefficient appears a Gaussian relationship with *h*.

1. Introduction

Solid particle erosion is inevitable in pipeline transportation with the working fluids containing solid particles, such as pneumatic conveying [1–3]. It is also a key factor affecting the lifetime of piping components and costs industries millions of dollars each year [4].

In past decades, to obtain erosion characteristics, a large amount of investigation has been carried out on piping components such as pipes, elbows, sudden expansion, sudden contraction, and valves. Shirazi et al. [5] developed a simple semi-empirical procedure for the estimation of erosion in piping components, and demonstrated the procedure for a tee and an elbow. Gabriel et al. [6] and Carlos et al. [7] revealed the effects of sand particle concentrations on the erosion of an elbow by simulations. Hanson et al. [8], Niu et al. [9], McLaury et al. [10,11], Akilli et al. [12], Yong Quek et al. [13] and Brown [14] also discussed the erosion in elbows by using simulation and experimental methods. Lee et al. [15] used the Eulerian approach to predict erosion in a boiler tube. Habib et al. [16–18] used the CFD method to investigate the effect of fluid flow and geometry on the erosion of a pipe contraction. Nemitallah et al. [19] indicated the effects of flow velocity, particle size, and pipe material on the downstream erosion of a sharp-edged orifice. Shabgard et al. [20] investigated the microstructural erosion features and material removal mechanisms of AISI H13 core boxes using experimental methods. Nøkleberg and Søntvedt [21] developed a model, which verified with experimental results, to estimate the erosion and lifetime of chokes valves. Forder et al. [22] presented a computational fluid dynamics erosion model and predicted erosion rates within oilfield control valves. McLaury et al. [23] performed a computational study to examine the erosion in a choke geometry; they demonstrated that abrupt changes in a fitting can result in regions of high erosion. Wallace et al. [24] used a Eulerian–Lagrangian model to examine erosion in two choke valves.

Cavities (Fig. 1) are one of the basic structures in pipe systems (such as in double flat gate valves). But only a few studies exist concerning particle erosion in cavities, including our own previous studies. Postlethwaite and Nesic [25] tested the erosion in an ideal cavity (where the height of the leading wall is equal to that of the aft wall) using silica sand. Wong et al. [26] investigated the erosion in a vertical ideal annular cavity (i.e., where the angle between the gravity force and the tube direction, φ, is 0°) using CFD and experimental methods. We also conducted both experimental and numerical studies investigating the characteristics of erosion in horizontal ($\varphi = 90°$) cavities. The effects of the height difference between the leading wall and aft wall on particle distribution and erosion have been analyzed [27,28].

From the above review, it is believed that previous studies have only focused on horizontal and vertical cavities. However, cavities have various orientations in process industries. Therefore, this study investigates gas-solid flow properties and erosion characteristics in inclined cavities

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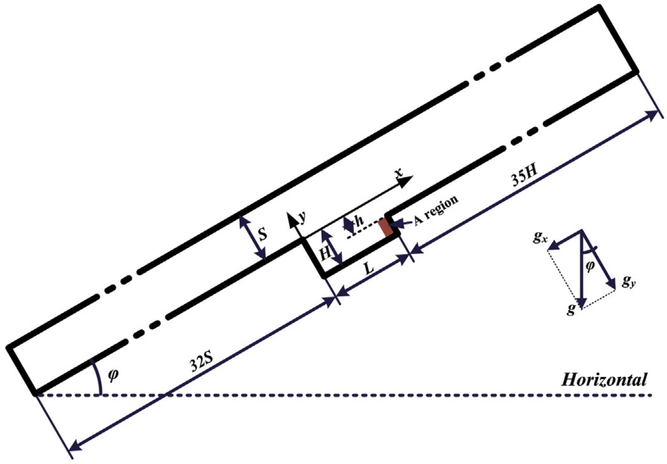

Fig. 1. Schematic structure of the computational domain.

(Fig. 1). The Eulerian-Lagrangian simulation method is applied. The effects of the inclination angle (φ) on gas flow, particle distribution, and erosion of the aft wall are discussed.

2. Problem statement

The problem considered is that of solid particle erosion in an inclined cavity. In accordance with our previous study [27], a 2D computational domain is used in this paper, as shown in Fig. 1. The flow domain consists of a cavity structure and two extension tubes. The heights of the upstream tube (S) and the leading wall (H) are 40 mm and 26.7 mm, respectively. According to the upstream length function of pipe turbulent flow, and referred to the two phase studies [29,30], the tube length upstream the cavity (L_{up}) was set as 32S. Meanwhile, the velocity profiles at the inlet of the cavity for L_{up} of 32S and 150S were also compared, and the results indicated that the upstream length of 32S is reasonable for present simulations. The tube length downstream of the cavity was set as 35H. The length of the cavity (L) was three times of H. The top point of the leading wall was set as the origin of the coordinates. Discussed height differences (h) were 0, 0.1H, 0.2H, 0.3H, 0.4H, 0.5H, 0.6H, and 0.8H. The inclination angle (φ) varied from 0° to 90°. Air at 25 °C is regarded as the carrier fluid. The working pressure is assumed as 1.01×10^5 Pa. The average gas velocity at the inlet was 9.3 m/s (i.e., the centerline velocity was 10.5 m/s when the flow developed fully). As the Mach number was far <0.3, the carrier fluid was set as incompressible. The density and the dynamic viscosity of air were set as 1.225 kg/m^3 and 1.79×10^{-5} Pa s, respectively. Stokes numbers (St) directly represent the following behaviors of particles with carrier fluid. The change of St will affect the distribution of particles and particle erosions [27,28,31]. Thus, to investigate the effect of St, diameters of 15, 50, and 150 μm were employed. According to Fessler and Eaton [32], the corresponding Stokes numbers (St) are 0.12, 1.2, and 9.1 (details are presented in our previous study [27]). The density of particles is 2500 kg ∕ m^3. The investigated particle mass loading ratio is 0.2, that the volume fraction (α_p) of loading particles is 0.0098% (i.e. 98 ppm by volume). The pipe material was set as carbon steel, and the Brinell hardness number was 140.

3. Simulation modeling

For the investigated cases, there are two high particle density regions inside the cavity: the bottom region of the cavity and the region near the aft wall. For the bottom region, particle velocities are extremely small. So whether consider particle collisions or not, motions of particles in this region do not impact the distribution of particles in the area away from the bottom wall, and also have no effect on the erosion of the aft wall. For the region near the aft wall, the largest local maximum volume fraction is about 0.1% for the discussed cases. According to Hugo [33], two-way coupling is considered a reasonable approach for $\alpha_p \le 0.1\%$. Therefore, particle collisions were neglected in present simulations, and two-way Eulerian-Lagrangian simulation method was used to predict the erosion of the aft wall within the cavity structure.

There are three main models in the present simulation as follows: the continuous phase model used for the prediction of the carrier fluid flow-field; the particle tracking model used for the calculation of particle trajectories; and the erosion model used for the determination of degree of erosion. This study is the follow-up research of our previous work [27]. The simulation method and the simulation procedure of this study are the same as that of our previous work. Thus, the simulation method and the procedure are described briefly in this study, further details were given in our previous paper.

3.1. The continuous phase model

The dynamics of incompressible flow were solved using the incompressible unsteady Reynolds-Averaged Navier-Stokes equation. The turbulence is calculated by the shear-stress transport (SST) model.

3.2. The particle tracking model

Particle trajectories were calculated using Newton's second law. As the Reynolds number is large in the present study, the Magnus lift force was not considered. The high value of ρ_p/ρ implies that the pressure gradient force and the virtual mass force were small and were therefore neglected. The Basset history force was ignored due to the low particle acceleration in simulations. By the magnitude analysis, it is found that the Saffman lift force was two orders of magnitude smaller than the drag force. Thus, the Saffman lift force on particles was also neglected. Under these assumptions, only drag and gravitation forces were used in the present calculations, shown as Eq. (1). The Random Walk Model (RWM) was also adopted for the calculation of the turbulent dispersion of particles.

$$\frac{d\boldsymbol{V_p}}{dt} = \boldsymbol{F_D} + \left(1 - \frac{\rho}{\rho_p}\right)\boldsymbol{g} \tag{1}$$

where the first term on the right-hand side is the drag force, and the second term is the gravity force.

Particle-wall interaction plays an important role in the calculation of particle trajectories. Hence, the coefficients of restitution (e_t, e_n) presented by Grant [34] were used to describe the collision and rebound performance between particle and wall.

$$e_n = 0.993 - 1.76\theta + 1.56\theta^2 - 0.49\theta^3 \tag{2}$$

$$e_t = 0.988 - 1.66\theta + 2.11\theta^2 - 0.67\theta^3 \tag{3}$$

where θ is the impact angle of the particle.

Table 1
Erosion model empirical constants for carbon steel (dry surface) and aluminum [36].

Constant	Carbon steel	Aluminum
C	$1.22 \times BH^{-0.59}$	1.865×10^{-6}
α	15 deg	10 deg
a	-3.34×10^{-4}	−34.79
b	1.79×10^{-4}	12.3
w	1	5.205
X	1.239×10^{-5}	0.147
Y	-1.192×10^{-5}	−0.745
Z	2.167×10^{-5}	1