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An erosion model for the discrete element method

Yongzhi Zhao*, Huaqing Ma, Lei Xu, Jinyang Zheng

Institute of Process Equipment, College of Energy Engineering, Zhejiang University, Hangzhou 310027, China

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ABSTRACT

A shear impact energy model (SIEM) of erosion suitable for both dilute and dense particle flows is proposed based on the shear impact energy of particles in discrete element method (DEM) simulations. A number of DEM simulations are performed to determine the relationship between the shear impact energy predicted by the DEM model and the theoretical erosion energy. Simulation results show that nearly one-quarter of the shear impact energy will be converted to erosion during an impingement. According to the ratio of the shear impact energy to the erosion energy, it is feasible to predict erosion from the shear impact energy, which can be accumulated at each time step for each impingement during the DEM simulation. The total erosion of the target surface can be obtained by summing the volume of material removed from each impingement. The proposed erosion model is validated against experiment and results show that the SIEM combined with DEM accurately predicts abrasive erosions.

Introduction

In equipment that contains solid particle flow, the impact between the particles and the wall of the equipment will cause abrasive erosion, which is a very common phenomenon in industrial fields such as chemical, energy, mining, pharmacy, and agriculture (Edwards, McLaury, & Shirazi, 2001; Johansson et al., 2004; Talia, Lankarani, & Talia, 1999). In the chemical and energy industries, problems caused by erosion frequently arise in equipment such as boiler tubes exposed to fly ash (Talia et al., 1999), tubes in fluidized bed combustion (He, Zhan, Zhao, Lu & Schlaberg, 2009; Johansson et al., 2004), gas turbine blades (Talia et al., 1999), and pneumatic conveying pipes (Edwards et al., 2001). Generally, there are two ways to control the erosion: selecting better materials for the equipment, and selecting proper working conditions (Edwards et al., 2001). Accurately predicting the location and magnitude of erosion in the equipment is necessary to prevent the failure of devices and reduce economic losses. Many industries have been developing reliable tools to solve the problem to save maintenance time and resources (Pereira, de Souza, & de Moro Martins, 2014).

To accurately predict abrasive erosion, we need to investigate the motion of the particles and develop a particle scale erosion model. However, though the characteristics of particles are similar to those of solids or fluids, particle motion is much more complex (Jiang, Zhao, Liu, & Zheng, 2011). It is difficult to describe particle motion with a continuum model because of the discrete nature of granular materials. By modeling the particle motions like molecules, the discrete element method (DEM) (Cundall & Strack, 1979) has been recognized as an effective tool to investigate the physics of granular materials because it can calculate the motion and micro-scale behavior of each particle (Chu & Yu, 2008; Cundall & Strack, 1979; Jiang et al., 2011; Tsuji, Kawaguchi, & Tanaka, 1993). For particles carried by fluids like air, oxygen, or other gases used in chemical industrial processes, the motion of the particles is coupled to the fluid flow. It is necessary to adopt the coupled computational fluid dynamics and discrete element method (CFD–DEM) method (Chu & Yu, 2008; Tsuji et al., 1993) to simulate the two-phase flow in these processes. This method has effectively simulated complex fluid–solid flows (Chu & Yu, 2008), such as the gas–solid flows in pneumatic conveying pipes (Chu & Yu, 2008; Kuang, Li, Zou, Pan, & Yu, 2013; Stratton & Wensrich, 2011), gas cyclone separators (Chu, Wang, Xu, Chen, & Yu, 2011; Chu, Wang, Yu, & Vince, 2009, Chu, Wang, Yu, & Vince, 2012; Chu & Yu, 2008), and fluidized beds (Chu & Yu, 2008; Di Maio, Di Renzo, & Trevisan, 2009; Nakamura, Kondo, & Watano, 2013; Nakamura, Tokuda, Iwasaki, & Watano, 2007; Pei et al., 2013; Wu, Ouyang, Yang, Li, & Wang, 2012; Yang, Luo, Fang, & Fan, 2013; Zhao, Liu, Cui, & Takei, 2010; Zhao, Cheng, Wu, Ding, & Jin, 2010; Zhou, Pinson, Zou, & Yu, 2011).

* Corresponding author.
E-mail address: yzzhao@zju.edu.cn (Y. Zhao).

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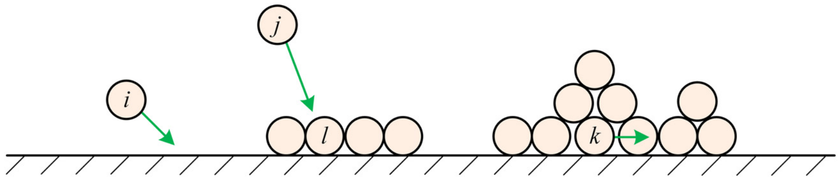

Fig. 1. Collisions between particles and surfaces that result in erosion.

The erosion mechanism at the particle scale has been experimentally investigated (Bitter, 1963a,b; Finnie, 1960; Neilson & Gilchrist, 1968; Sheldon & Finnie, 1966a), and several single-particle erosion models have been proposed (Lyczkowski & Bouillard, 2002), such as Finnie's ductile erosion model (Finnie, 1960), Bitter's combined ductile and brittle erosion model (Bitter, 1963a,b), Neilson and Gilchrist's combined ductile and brittle erosion model (Neilson & Gilchrist, 1968), and Sheldon and Finnie's 90° brittle erosion model (Sheldon & Finnie, 1966a). Among them, Finnie's ductile erosion model (Finnie, 1960) has been widely used in erosion prediction of ductile materials. For predicting erosion using Finnie's erosion model (Finnie, 1960), the impact velocity and angle of each particle need to be calculated and recorded when the particle first contacts the target surface, then the erosion can be calculated. Because only the first contact is considered in the model, it can calculate the erosion caused by direct impact (such as particle *i* in Fig. 1) but not the erosion caused by non-direct impact (such as particle *j* in Fig. 1, which will hit particle *l* but not the surface) or sliding friction (such as particle *k* in Fig. 1). In Finnie's erosion model, the erosion caused by non-direct impact will be ignored because the particle does not contact the surface, and the erosion caused by sliding friction cannot be calculated because it is not a first-time contact. Therefore, Finnie's erosion model is only suitable for dilute particle flow, but not for dense particle flow that occurs in dense fluidized beds or high-concentration pneumatic conveyers in which non-direct impacts and sliding occur much more frequently than direct impacts.

In order to predict the erosion in devices that contain dense particle flow, a new particle-scale erosion model is needed. Ashrafizadeh and Ashrafizadeh (2012) recently investigated the impact of solid particles on a surface with DEM simulations and compared the simulation results with experimental data (Zhang, Sazonov, Kent, Dixon, & Novozhilov, 2001). They found that the shear impact energy (the tangential component of the impact energy subjected on the target surface by the particle) is relevant to the cutting erosion. This indicates that the erosion can be predicted from the shear impact energy in DEM simulations. In this work, an erosion model for DEM termed the shear impact energy model (SIEM) is proposed based on the relationship between the shear impact energy and the erosion. Compared with Finnie's erosion model, the new model is suitable for both dilute and dense particle flows because the impact energy of direct, non-direct, and sliding impacts can be obtained. The accuracy of the model is validated by comparing simulation results with the experimental results.

Erosion model

When a hard particle, which can be considered a rigid body, strikes the surface of a ductile material, it will cut into the surface and remove some material, as shown in Fig. 2(a). According to Finnie's erosion theory (Finnie, 1960, 1972), the expression for the volume of material removed is

$$W = \frac{c}{\varphi}\frac{mv^2}{2}\frac{1}{p}f(\alpha), \tag{1}$$

where $c = 1/2$, $\varphi = 2$ according to Finnie's experimental results (Finnie, 1960, 1972), m is the mass of the particle, and v is the velocity of the particle. p is the plastic flow pressure of the erosion surface, which is generally about one–five times the value of the Vickers hardness of the target surface according to the experimental data of Finnie, Wolak, and Kabil (1967). f is a function of the impact angle α and can be described as follows,

$$f(\alpha) = \begin{cases} \frac{2}{K}\left[\sin(2\alpha) - \frac{2}{P}\sin^2(\alpha)\right] & \tan(\alpha) \le \frac{P}{2} \\ \frac{P}{K}\cos^2(\alpha) & \tan(\alpha) > \frac{P}{2} \end{cases}, \tag{2}$$

where K is the ratio of normal to tangential force, which is set as the reciprocal of the friction coefficient in the DEM simulations. P can be described as:

$$P = \frac{K}{1 + mr^2/I}, \tag{3}$$

where r is the average particle radius and I is the moment of inertia of the particle about its center of gravity. From Eq. (2) it can be shown that the maximum volume removal occurs when $\tan(2\alpha) = P$ while the two expressions are equal at the slightly higher angle given by $\tan(\alpha) = P/2$.

In this paper, we focus on the erosion caused by spherical particles. For spherical particles, the moment of inertia I is $2mr^2/5$ and P is $2K/7$. Eqs. (1) and (2) then become:

$$W = \frac{1}{4}\frac{mv^2}{2}\frac{1}{p}f(\alpha), \tag{4}$$

where

$$f(\alpha) = \begin{cases} \frac{2}{K}\left[\sin(2\alpha) - \frac{7}{K}\sin^2(\alpha)\right] & \tan(\alpha) \le \frac{K}{7} \\ \frac{2}{7}\cos^2(\alpha) & \tan(\alpha) > \frac{K}{7} \end{cases}.$$

The maximum volume removal occurs when $\tan(2\alpha) = 2K/7$ and the two expressions are equal at the angle given by $\tan(\alpha) = K/7$.

From the perspective of energy conversion, Eq. (4) can be written as follows,

$$W = \frac{E_{\text{Finnie}}}{p}, \tag{5}$$

where E_{Finnie} represents the impact energy that is converted to erosion in Finnie's model, that is

$$E_{\text{Finnie}} = \frac{1}{4}\frac{mv^2}{2}f(\alpha), \tag{6}$$

where

$$f(\alpha) = \begin{cases} \frac{2}{K}\left[\sin(2\alpha) - \frac{7}{K}\sin^2(\alpha)\right] & \tan(\alpha) \le \frac{K}{7} \\ \frac{2}{7}\cos^2(\alpha) & \tan(\alpha) > \frac{K}{7} \end{cases}.$$

According to Ashrafizadeh & Ashrafizadeh (2012), E_{Finnie} is related to the shear impact energy. However, it was difficult to calculate the shear impact energy during the impingement either by