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Predicting discharge dynamics of wet cohesive particles from a rectangular hopper using the discrete element method (DEM)

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ABSTRACT

Accurate prediction of the discharge rate from hoppers is important in many industrial processes involving the handling of granular materials. The present work investigates the parameters affecting the discharge rate of a *wet* cohesive system from a quasi-3-D, rectangular hopper using the discrete element method (DEM). The cohesion between the particles is described by a pendular liquid bridge force model and the strength of the cohesive bond is characterized by a Bond number. The Beverloo correlation is applied to cohesive systems by modifying the Beverloo constant as a function of Bond number. The predictions obtained from this modified correlation fit the simulation data reasonably well. In addition, the effect of hopper angle in cohesive systems is shown to follow a trend similar to cohesionless systems, where the discharge rate is insensitive to changes in hopper angle except below a critical angle (with respect to the vertical) where the discharge rate increases rapidly. This critical angle of flow decreases with increasing cohesion.

1. Introduction

Hoppers are widely used during the processing and handling of granular materials. One of the major industrial problems in using hoppers is obtaining reproducible and consistent particle discharge flow rates, which is associated with the complex flow patterns of granular materials inside the hopper. Cohesive granular materials further complicate this problem and make difficult the accurate prediction of discharge rate which is necessary for the dependable design and operation of hoppers.

In this work, a physically meaningful computational approach is developed for predicting the discharge behavior of wet, cohesive, mono-disperse granular materials from a rectangular hopper. Specifically, a rectangular, wedge-shaped hopper is chosen for studying the discharge behavior of particle systems in the presence of liquid bridges. Different parameters that may affect the discharge rate are studied including the degree of cohesion (characterized by the Bond number and liquid content), hopper angle and outlet width. Discrete element method (DEM) modeling, which has become a common approach for studying such problems, is used as the tool for investigating the effect of these parameters. DEM models consider the granular material to be a collection of discrete solid particles which move according to Newtonian mechanics.

Previous work by Anand et al. (2008) investigated hopper discharge rate with *cohesionless* particles. The application of DEM to this problem significantly enhanced the understanding of the particle and hopper properties affecting the discharge rate. For example, in a cohesionless system the coefficient of restitution, hopper width and particle diameter have negligible effect. Also, the DEM results compared favorably with the predictions from various experimental correlations reported in the literature for the effects of hopper angle, outlet width and particle size distribution on discharge rate. In this present study, we probe the discharge rate in a *wet*, *cohesive* system by including the cohesive model of Mikami et al. (1998) in the DEM code described in Anand et al. (2008).

2. Background

Cohesion is the attractive force between particles, and if cohesion is significant, substantial deviation from the free-flowing behavior of particulate systems is evident. Cohesion between

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particles can originate from several sources including van der Waals forces, electrostatic forces, and liquid bridges (capillary forces). For particles larger than several hundred microns, which are also free of electrostatic charge, the most important source of cohesion is liquid bridges (Seville et al., 2000). This cohesion force is the focus of this study.

When a quantity of liquid is introduced between particles, various regimes of liquid distribution are possible, depending upon the degree of saturation. These are the pendular, funicular, capillary and droplet regimes. For low liquid content, pendular liquid bridges are formed as shown in Fig. 1. With pendular liquid bridges, the interaction between the particles is always binary. As the liquid content increases, the liquid bridges are not independent of each other and the pendular liquid bridges begin to merge as the system transitions to the funicular and capillary regimes. At very high liquid content, the droplet regime is reached and the particles are essentially immersed in the liquid. For the present study, we only consider the *pendular* regime.

3?A3B2 tlsb=-0.02w?>The stable, smooth liquid bridge formed between two spherical particles results in an attractive force between them. This force, in the case where gravitational distortion of the liquid bridge is negligible, contains two components: (1) the axial component of the surface tension acting on the three-phase contact line, and (2) the hydrostatic force due to the pressure deficiency in the bulk of the liquid.

The theoretical analysis of such a liquid bridge force has been the focus of previous studies (see, for example, Mehrotra and Sastry, 1980; Lian et al., 1993; Willett et al., 2000). Lian et al. (1993) derive the liquid bridge force as a function of the surface tension, half-filling angle, contact angle, and particle radius. However, to implement this force model into a DEM code in a computationally efficient manner, an explicit relationship between the force, liquid bridge volume, and contact angle and particle separation distance is needed. The regression expressions generated by Mikami et al. (1998) provide just this sort of relation. Mikami et al. (1998) developed a dimensionless cohesive force correlation for a pendular bridge spanning two equal-sized spheres as a function of the liquid volume and particle separation distance:

$$F_{lb} = \pi\gamma R\left[\exp\left(A\frac{h}{R}+B\right)+C\right] \tag{1}$$

$$A = -1.1\left(\frac{V}{R^3}\right)^{0.53} \tag{2}$$

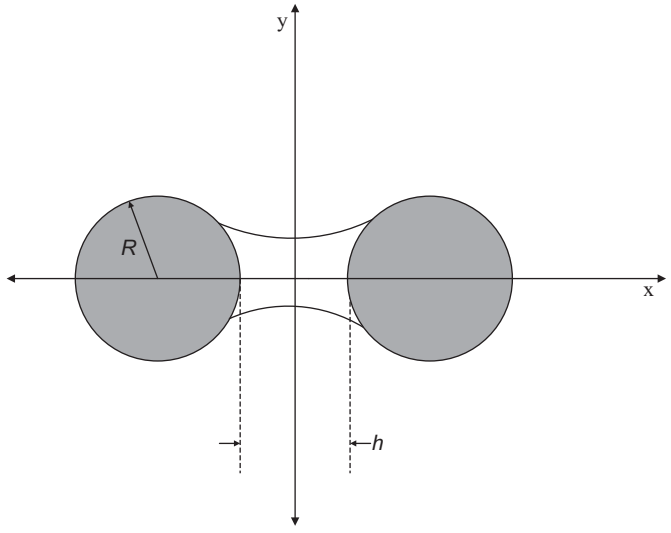

Fig. 1. Representation of the liquid bridge formed between particles of equal size.

$$B = \left(-0.34\ln\left(\frac{V}{R^3}\right)-0.96\right)\beta^2 - 0.0019\ln\left(\frac{V}{R^3}\right)+0.48 \tag{3}$$

$$C = 0.0042\ln\left(\frac{V}{R^3}\right)+0.078 \tag{4}$$

where γ is the surface tension of the liquid, R is the radius of the sphere, β is the contact angle of the liquid with the particle, h is the separation distance, and V is the liquid volume associated with the liquid bridge. The constants A–C are dimensionless regression parameters. Mikami et al. (1998) also presented similar regression expression for a sphere-wall liquid bridge interaction.

Another important parameter for the liquid bridge force between particles is the bridge rupture distance $h_{rupture}$. The rupture distance is the maximum separation distance between the particles for which the liquid bridge is stable. Experiments by Mason and Clark (1965) show that the rupture distance for any meridianal profile of the liquid bridge varies linearly with contact angle β and $V^{1/3}$. Additional theoretical considerations by Lian et al. (1993) have yielded the following specific relationship between the rupture distance and the liquid bridge volume and the contact angle:

$$h_{rupture} = (1+0.5\beta)V^{1/3} \tag{5}$$

In addition to the liquid bridge force, particles are subject to a viscous, resistance force F_{vf} resulting from the squeezing out and pulling in of liquid between the two closely spaced particle surfaces. Assuming rigid spheres, the viscous squeeze film force in the normal direction is:

$$F_{vf} = 6\pi\eta R^* v_n \frac{R^*}{h} \tag{6}$$

$$\frac{1}{R^*} = \frac{1}{R_1}+\frac{1}{R_2} \tag{7}$$

where η is the viscosity of the liquid, v_n is relative speed between the particles, and R^* is the effective particle radius (Lian et al., 1998). A minimum value for h, corresponding to the combined asperity height of the two surfaces, in this case equaling 1/100th of the smaller particle diameter, is employed to keep the viscous force bounded. It has been observed in this work and in the work by McCarthy (2003) that the results are insensitive to a two order change in the magnitude of the chosen asperity value. A similar tangential viscous force may also be derived, but previous studies have shown that this force has a negligible effect on particle motion (Hsiau and Yang, 2003). The typical value of the liquid bridge force in the current simulations is 50 dyn whereas the typical value of the viscous force is 4–5 dyn, which is at least an order of magnitude less than the liquid bridge force.

An important parameter for characterizing the relative cohesiveness of a system is the Bond number, *Bo*, which is defined as the ratio of the maximum cohesive force acting on a particle, F_c, to the gravitational force acting on the particle, W:

$$Bo = \frac{|F_C|}{W} = \frac{2\pi R\gamma}{\frac{4}{3}\pi R^3\rho g} = \frac{3\gamma}{2R^2\rho g} \tag{8}$$

where γ is the surface tension of the liquid, R is the radius of the particle, ρ is the density of the particle, and g is gravitational acceleration (Nase et al., 2001). As the Bond number of the system increases, the cohesiveness of the system increases. For example, Bo=0.25 represents a maximum cohesive force on a particle that is 25% of the particle's weight.