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Insights into the granular flow in rotating drums

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ABSTRACT

Scaling relations for the velocity profile and circulation time, which can be used in design and scale-up, are of great importance in rotating drums. We conducted simulations by discrete element method at various operating conditions (which covers both rolling and cascading regimes) for spherical and non-spherical particles. New scaling relations were proposed for evaluating and fully characterize velocity profile and circulation time in both rolling and cascading regimes. Using dynamic angle of repose, effect of shape was included in these correlations to extend them to spherical and non-spherical particles. Simulation results can satisfactorily reproduce experimental measurements. Visual results show that transition from rolling to cascading regime depends not only on Froude number, fill level and particle size, but also on the particle shape. The surface velocity is scaled with peak velocity and half chord length and its profile is asymmetric with the maximum occurring after the mid-chord position for all simulations. We obtained a correlation for the peak velocity based on our simulations as well as available experimental data in literature. We also found the velocity profiles along the bed depth in active and passive layers. Our results show that the circulation time of particles follow a log-normal distribution. The mean circulation time decreases with rotation speed and drum diameter and increases with fill ratio. This value is greater for spherical particles compared to non-spherical particles. Correlations are also proposed for mean and standard deviation of the circulation time.
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1. Introduction

Rotating drums have a wide range of applications in industries like food, pharmaceutical, agricultural, metallurgical, chemical and solid waste treatment (Ndiaye et al., 2010). They possess good heat and mass transfer characteristics which make them suitable for being used in many processes like mixing of powders, drying, calcination, coating, granulation (size enlargement), size reduction, pyrolysis and chemical reactions (Fantozzi et al., 2007). They are able to handle various types of feeds (wet or dry, fine or course granules, spherical and non-spherical). These make them superior to similar equipment like fluidized beds. Although their geometry and operation are rather simple, the granular flow in these drums is complex and is not understood completely. The granular flow in these drums becomes more complex when the process involves non-spherical particles, size enlargement or reduction.

Table 1 shows various studies on granular flow in rotating drums. Concerning the application of the rotating drum, different aspects of granular flow were studied. For mixing purposes, mixing or segregation extent, characterization of different mechanisms of mixing and segregation and mixing time are addressed (Pandey et al., 2006c). For coating and granulation purposes, distributions of circulation time, surface time/velocity of particles, particles exposure area and orientation toward spray nozzle are investigated and used to assess the quality of coated particles in the final product (Kalbag and Wassgren, 2009; Pandey et al., 2006a). In some cases, a spray model is assumed and the Monte-Carlo technique is used to obtain the distribution of coating mass

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Nomenclature

CL_i	contact list of particle i
D	diameter of drum (m)
$\vec{F}_{ij}$	contact force between particles i and j (N)
I_i	moment of inertial (kg m^2)
L	half of chord length (m)
$\vec{M}^r_{ij}$	rolling resistance torque of particle i (N m)
$\vec{M}^t_{ij}$	tangential torque of particle I (N m)
R_i	particle radius (m)
X,Y	two dimensional coordinates aligned with bed surface
d_p	particle diameter (m)
$\vec{f}^n_{ij}$	contact force in the normal direction (N)
g	acceleration of gravity (m s^{-2})
m_i	particle mass (kg)
t	time (s)
u_{max}	peak velocity at the bed surface (m s^{-1})
u_{surf}	surface velocity (m s^{-1})
$\vec{v}_i$	particle translational velocity (m s^{-1})
$\vec{\omega}_i$	particle rotational velocity (rad s^{-1})
$\vec{x}_i$	position vector of particle (m)

Greek letters

α,α_0	dynamic and static angle of repose (°)
β	asymmetry factor
φ	fill ratio
λ_0	depth at which velocity becomes zero (m)
μ, μ_r	dynamic and rolling friction factors
ω	drum rotation speed (rad s^{-1})
$\dot{\gamma}$	shear rate (s^{-1})

among particles (inter-particle variability) and on each particle (intra-particle variability) (Freireich and Wassgren, 2010). The information required to Monte-Carlo modeling can be obtained from experimental measurements (Kandela et al., 2010) or discrete element method (DEM) simulations (Freireich et al., 2011).

Another aspect of the granular flow in rotating drums is velocity profile of particles at different flow regimes. Depending on the fill level and Froude number, six different flow regimes, namely slipping, slumping, rolling, cascading, cataracting and centrifuging can be observed. Most industrial drums operate in rolling or cascading regimes due to low energy consumption and providing a good mixing. The velocity profile of particles was analyzed to determine the rate of material transport, residence time, heat and mass transfer rates (Chaudhuri et al., 2006; Heydenrych et al., 2002), and developing scale-up relations (Mueller and Kleinebudde, 2007). Experiments and models are mostly available in the rolling regime. There are two distinct layers in the rolling regime: active (cascading) and passive layers. In the passive layer, beneath the active layer, particles move with the drum wall as a solid body and enter the thin active layer. In the active layer, particles flow to the down of the bed surface due to gravity. The velocity profile and the thickness of active layer of spherical dry particles (Alizadeh et al., 2013; Jain et al., 2002; Khakhar et al., 1997; Santomaso et al., 2003), non-spherical particles (Dubé et al., 2013), and wet particle (McCarthy et al., 2000) have been investigated using experimental measurements in rolling regime. Besides, theoretical (Boateng, 1998; Ding et al., 2001b; Liu et al., 2006; Mellmann et al., 2004; Yan Liu and Specht, 2010) and semi-empirical (Cheng, 2012; Cheng et al., 2011; Weir et al., 2005) correlations have also been developed. Although the flow behavior of particles has been well studied in literature, a few studies can be found on the cascading regime (Pandey et al., 2006a; Sandadi et al., 2004; Suzzi et al., 2012). In addition, effect of particle shape is not explicitly known on the flow behavior of particles.

We conducted a set of DEM simulations in the present study to characterize the flow behavior of both spherical and non-spherical particles. Effects of drum rotational speed, fill level, drum size and particle size and shape on the velocity profile and circulation time of particles were considered. The operating conditions in simulations cover both rolling and cascading regimes. We first validated DEM results using available experimental data in literature. Then, we characterized velocity profile, active layer thickness and circulation time. Our aim was to accomplish two main goals:

- To test whether available correlations, which belong to either rolling or cascading regime, are applicable to both regimes; and in some cases, to extend that correlation in a way that it provides accurate predictions in both regimes.
- To include effect of particle shape in the correlations in a way that they can be utilized for both spherical and non-spherical particles.

2. Model description and simulations

2.1. Model equations

Particles are tracked individually in the DEM. Translational and rotational motions of each particle are described by the Newton's second law of motion and Euler's law, respectively. Two main approaches can be used to describe interactions between particles: hard-sphere (event-driven) and soft-sphere (time-driven). We used the soft-sphere approach in which particles can have partial overlaps and hence, a particle can have contacts with multiple particles—which is the case for most of granular flows. Equations of motions for a spherical particle are:

$$m_i \frac{d\vec{v}_i}{dt} = m_i \frac{d^2\vec{x}_i}{dt^2} = \sum_{j \in CL_i} \vec{F}_{ij} + m_i \vec{g} \quad (1)$$

$$(2) I_i \frac{d\vec{\omega}_i}{dt} = \sum_{j \in CL_i} (\vec{M}^t_{ij} + \vec{M}^r_{ij})$$

Various force–displacement laws have been developed to calculate contact forces between particles, $\vec{F}_{ij}$ (Di Renzo and Di Maio, 2004; Kruggel-Emden et al., 2009, 2010). We used the linear–viscoelastic force–displacement model for both normal and tangential directions combined with Coulomb's friction law and considering limited tangential displacement (more information is given in Kruggel-Emden et al., 2008b). Rotational motion of a spherical particle is affected by the tangential torque, $\vec{M}^t_{ij}$, produced by inter-particle contacts and rolling friction torque, $\vec{M}^r_{ij}$, which opposes the rotation of particle which are calculated by:(3)$\vec{M}^t_{ij} = R_i \vec{n}_{ij} \times \vec{F}_{ij}(4)\vec{M}^r_{ij} = -\mu_r R_i \left|\vec{f}^n_{ij}\right| \frac{\vec{\omega}_i - \vec{\omega}_j}{\left|\vec{\omega}_i - \vec{\omega}_j\right|}$

In addition to particle–particle interaction, particle–wall interaction also exists in the system. The same formulation was used for particle wall intreations (contact force and friction law). To approximate the non-spherical shape of

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