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Effect of wall roughners on cross-sectional flow characteristics for non-spherical particles in a horizontal rotating cylinder

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ABSTRACT

Discrete-element-method (DEM) simulations have been performed to investigate the cross-sectional flow of non-spherical particles in horizontal rotating cylinders with and without wall roughners. The non-spherical particles were modeled using the three-dimensional super-quadric equation. The influence of wall roughners on flow behavior of grains was studied for increasing particle blockiness. Moreover, for approximately cubic particles (squareness parameters [5 5 5]), the rotational speed, gravitational acceleration and particle size were altered to investigate the effect of wall roughners under a range of operating conditions. For spherical and near-spherical particles (approximately up to the squareness parameters [3 4 4]), wall roughners are necessary to prevent slippage of the bed against the cylinder wall. For highly cubic particle geometries (squareness parameters larger than [3 4 4]), wall roughners resulted in a counter-intuitive decrease in the angle of repose of the bed. In addition, wall roughners employed in this study were demonstrated to have a higher impact on bed dynamics at higher rotational speeds and lower gravitational accelerations. Nevertheless, using wall roughners had a comparatively small influence on particle-flow characteristics for a bed composed of finer grains.

1. Introduction

Rotating cylinders or kilns are widely employed in industry, ranging from the pharmaceutical, food, and agricultural industries to the chemical industry (Ait Aissa, Duchesne, & Rodrigue, 2010; Fontes, de Sousa, Souza, Bezerra, & Benachour, 2011; Kaunisto, Nilsson, & Axelsson, 2009; Prasanna Kumar, Srivastava, & Nagesh, 2009; Scott et al., 2008; Yamane, Sato, Tanaka, & Tsuji, 1995). A fundamental understanding of the underlying physics of such systems is therefore not only of academic interest, but also relevant for industrial applications. Granular materials are typically opaque, however, making the acquisition of experimental measurements in such systems, *e.g.* using conventional high speed optical imaging techniques, very challenging (Müller et al., 2007a, Müller et al., 2007b; Holland et al., 2009; Third, Scott, & Scott, 2010; Third, Scott, Scott, & Müller, 2010). As an alternative, computational techniques, such as the discrete element method (DEM), can be applied as a tool to investigate the underlying physics of particle interactions and the dynamics within a bed of grains (Cleary & Sinnott, 2008; Bridgwater, 2010). The DEM is a particularly attractive modeling technique as it can provide both macroscopic and microscopic 'measurements' in granular systems and, importantly, enables the modeling of particles of various non-spherical shapes (Cleary, 2010).

So far, studies investigating the dynamics of horizontal rotating cylinders have mostly been devoted to beds composed of spherical particles (Zhu, Zhou, Yang, & Yu, 2008; Seiden & Thomas, 2011). For example, Lim et al. (2003) applied positron emission particle tracking (PEPT) techniques to measure how particles move in the active surface region during avalanches in a slowly rotating cylinder. The mean number of avalanches required for particles to traverse the active region of the bed were observed to vary with the rotational speed of the drum and ranged from approximately 4 at a low rotational speed to 1 at a high rotational speed. As the angular velocity of the rotating cylinder is increased, the bed enters the rolling flow regime, characterized by particles continuously flowing downward along the top layer of the bed and subsequently being transported upward along the periphery of the bed. The

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Notation

a, b, c	half-lengths of particle principal axes, m
d	diameter of volume-equivalent sphere, mm
g	gravitational acceleration, m/s^2
h	distance from the surface of a bed, m
H	filling height of a bed, m
k_{n_i}	normal stiffness of particle i, N/m
$k_{n_{ij}}$	effective normal stiffness, N/m
k_{n_j}	normal stiffness of particle j, N/m
k_{t_i}	tangential stiffness of particle i, N/m
$k_{t_{ij}}$	effective tangential stiffness, N/m
k_{t_j}	tangential stiffness of particle j, N/m
l	length of particle principal axes, m
m, n, p	squareness parameters of a super-quadric particle
N	total number of particles considered
r	radial distance from cylinder center, m
R	radius of a rotating cylinder, m
T	granular temperature, m^2/s^2
u_i	horizontal velocity of a particle, m/s
u_j	vertical velocity of a particle, m/s
u_x	particle horizontal velocity, m/s
u'_i	fluctuation of particle horizontal velocity, m/s
$\langle u_x \rangle$	averaged particle horizontal velocity, m/s
u_y	particle vertical velocity, m/s
u'_y	fluctuation of particle vertical velocity, m/s
$\langle u_y \rangle$	averaged particle vertical velocity, m/s
v	tangential velocity, m/s
v_n	relative velocity in the normal direction, m/s
v_t	relative velocity in the tangential direction, m/s
x, y	coordinates

Greek letters

δ	thickness of the flowing layer of a bed, m
δ'	thickness of the active region of a bed, m
δ_n	overlap between two colliding particles, m
δ_t	tangential displacement between two colliding particles, m
η_n	damping factor in the normal direction
η_t	damping factor in the tangential direction
γ	shear rate, s^{-1}
μ	coefficient of friction
ρ	particle density, kg/m^3
θ	dynamic angle of repose,$^\circ$
ω	rotational speed of a rotating cylinder, rpm

particle motion described here is widely believed to be categorizable into two regions: an active region, in which shear motion between neighboring layers of particles dominates, and a passive region, in which particles undergo rigid body rotation. Mellmann, Specht, & Liu (2004) proposed a mathematical model of this regime by considering mass and momentum balances and the specified initial conditions. This model predicts the main characteristics of rotating beds, *i.e.* the thickness of the flowing layer, the shape of the interface between the active and passive regions, the mass flow rates of both flow regions, and the velocity at the bed surface, as a function of rotational speed, fill level and cylinder diameter. Results from the model agreed well with experimental measurements performed over a wide range of bed materials, bed geometries, and operating conditions.

An important aspect of rotating cylinder that has received very little attention is the wall-slip condition close to the wall of rotating cylinders. Previously, Parker, Dijkstra, Martin, and Seville (1997) carried out PEPT experiments using 1.5 mm glass spheres in a cylinder of 136 mm diameter, and 3 mm glass spheres in cylinders of 100 and 144 mm diameters rotating with a speed in the range of 10–65 rpm. In most experiments, the velocity of the outermost layer of particles was considerably lower than that of the cylinder wall. Parker et al. (1997) attributed this 'slip' to the ability of the outermost particles to roll. Boateng and Barr (1997) performed an experimental study of the granular flow in a partially filled rotating cylinder using high-density polyethylene pellets, long grain rice, and commercial grade limestone. To prevent particle slippage near the wall, the cylinder wall was roughened with a coating of epoxy paint uniformly sprinkled with coarse Ottawa sand with an average size of 3.2 mm. The flow in the transverse plane was investigated for the three particle types and a range of fill levels and rotational speeds. At a speed of 3 rpm, the shapes of the tangential velocity profiles for beds of polyethylene pellets with a fill level of 3.3% and of long grain rice with a fill level of 10% were found to be comparable. However, because of particle slippage close to the wall, the measured velocity profile deviated considerably from the expected rigid body rotation in the passive region of the bed filled with long grain rice to a fill level of 10% operated at a rotational speed of 5 rpm. Furthermore, the extent of the shear layer increased with increasing rotational speed and decreased with increasing fill level. Using the DEM, Yamane, Nakagawa, Altobelli, Tanaka, & Tsuji (1998) studied steady-state particulate flow in a horizontal rotating cylinder filled with non-spherical particles. The non-spherical particles were modeled by 'gluing' together two spheres of equal diameter. The predicted tangential velocity profiles showed good agreement with MRI measurements. In a further study, Mustoe and Miyata (2001) employed super-quadrics to determine the effect of particle squareness on the dynamic angle of repose formed by cubic particles within a 2D horizontal rotating cylinder. The results showed that the dynamic angle of repose increases monotonically with particle squareness, having an upper limit of approximately 40°. Recently, Third, Scott, and Müller (2011) also investigated the tangential velocity profile of non-spherical particles within a horizontal rotating cylinder using the DEM by gluing spheres together. The tangential velocity profile obtained using non-spherical particles matched well with the expressions proposed by Nakagawa, Altobelli, Caprihan, Fukushima, and Jeong (1993) on the basis of magnetic resonance measurements, *i.e.* the tangential velocity profile along a radius perpendicular to the surface of the bed follows a quadratic relationship with the radial position in the active region and increases linearly in the passive region. In contrast, when spherical particles were simulated, a substantial slip between the particles and the cylinder wall was observed. Therefore, to prevent slippage, use of either wall rougheners or non-spherical particle shapes was proposed.

This study investigated the effect of wall rougheners on the dynamics of rotating cylinders filled with non-spherical particles. Additionally, we studied the influence of wall rougheners on the macroscopic particle dynamics under different rotational speeds, gravitational accelerations, and particle sizes. The aim of this paper is to highlight wall roughness and also particle shape on the dynamics of beds within rotating cylinders. As non-spherical particles are frequently encountered in industrial area and bed slippage has been vastly considered in the design of reactors, the study performed here is highly relevant to applications and thus of industrial importance.

2. Simulation methods

In this work, the DEM, originally developed by Cundall and Strack (1979), was used to simulate particle dynamics