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The kinematics of non-cohesive, sphero-cylindrical particles in a low-speed, vertical axis mixer

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HIGHLIGHTS

- The kinematics of sphero-cylindrical particles in a mixer are modeled.
- Increasing particle aspect ratio decreases particle velocities relative to blade.
- Increasing particle aspect ratio decreases overall bed solid fraction.
- Sphero-cylinders tend to align along the flow streamlines.
- Similarities exist with the flow of spheres, but some differences are observed.

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ABSTRACT

A discrete element method model is used to examine the velocity, solid fraction, and particle orientation fields of non-cohesive, sphero-cylindrical particles agitated in a vertical axis mixer for a range of particle aspect ratios and bed depths. The model is validated against experimental measurements of the rotating shaft torque. The particle trajectories within the bed are similar to those that have been reported previously for spheres, with a vortex circulating in the direction opposite of the blade rotation on horizontal planes of the bed. Increasing the particle aspect ratio generally decreases the particle velocities relative to the blade, implying reduced mixing. The solid fraction is largest just upstream of the blades and toward the base of the container for sphero-cylindrical particles. The smallest solid fractions are located in the wake region and at the bed's free surface. These results are generally consistent with those for spherical particles, although for spheres the solid fraction is smaller upstream of the blades near the container base. In general, larger particle aspect ratios decrease the overall bed solid fraction as well as the solid fraction uniformity. Particles with an aspect ratio larger than one have major axes that are offset between 10° and 20° from the flow streamlines. The degree of alignment between particles increases near boundary regions. In addition to the strong correlation between the particle principal orientation and velocity vectors, regions of larger velocity gradient magnitude result in smaller solid fractions and smaller degrees of three-dimensional alignment between particles.

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1. Introduction

Vertical axis mixers are commonly used in the processing of particulate materials. For example, high shear wet granulation is frequently performed in a vertical axis mixer geometry as is agitated filter drying of active pharmaceutical ingredients, albeit at different blade impeller speeds. These mixers typically consist of a roughly cylindrically shaped bowl, at the center of which is a vertical shaft with attached mixer blades. The rotating blades induce particle movement and, ideally, result in satisfactory mixing of the particle bed as well as other processing. In a high shear wet granulation process, for example, particle agglomeration is desired, although large granules, or lumps, are undesirable, while in an agitated filter dryer (AFD) the mixer blades should not only mix the bed, but also break up agglomerates while avoiding damage to individual particles.

The ubiquity of vertical axis mixers in industry has resulted in considerable research on how particles move in such a system. Numerous experimental and computational studies have been performed to investigate the influence of impeller speed, fill level, mixer size, blade angle, particle size distribution, and inter-particle friction and cohesion, many of which are discussed in Section 2. These studies have provided excellent insight into how particles generally behave in such systems; however, one important

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parameter that has yet to be investigated in depth is the influence of particle shape. Previous work, especially prior computational work, has assumed spherical particles. The focus of the current work is to examine how the aspect ratio of sphero-cylindrical particles, i.e., rod-like particles, influences the solid fraction, velocity, and particle orientation fields in a vertical axis mixer. Rod-like particles are of particular interest in the operation of pharmaceutical AFDs since the particles typically processed in such devices are often needle-shaped.

2. Background

There have been numerous studies, both experimental and computational, concerning particle movement and mixing in vertical-axis, low-shear and high-shear, bladed mixers (see, for example, Zhou et al., 2004; Stewart et al., 2001a, 2001b; Conway et al., 2005; Remy et al., 2010). These studies have demonstrated that particle movement depends upon a number of factors including blade speed, fill depth, particle cohesiveness, and inter-particle friction. Note that these previous studies have focused on the movement of spherical particles. Only the steady, periodic state of the powder bed is reported in this paper since the bed reaches this state after only a few impeller revolutions (Chandratilleke et al., 2009; Conway et al., 2005; Stewart et al., 2001a). Furthermore, the influence of cohesion and segregation will not be reviewed since the current work focuses on non-cohesive, identical particle behavior.

2.1. Flow patterns

Three general types of flow patterns have been observed in vertical axis, bladed mixers: heaping, bumping, and roping. Which behavior appears is a function of a number of parameters, but blade speed is one of the most significant, with heaping appearing at slower speeds, as would be found in an AFD, for example. Bumping and roping at faster speeds, which is more typical of high shear wet granulators. Since the present work focuses on low speed behavior, only the heaping regime is discussed here.

The heaping regime is characterized by a bed with heaps occurring near the blades and valleys located between the blades (refer to Fig. 1a). Particle movement in the bed is complex with particles avalanching down the surface of the heaps and forming re-circulating regions within the bed (Zhou et al., 2004; Stewart et al., 2001a, 2001b; Conway et al., 2005). Near the base of the mixer, particles move tangentially with the blades, with the largest speeds occurring immediately upstream of the blades. In the middle portion of the bed, particles generally follow the tangential movement observed in the deeper layers. Particles just upstream of the blade also move radially inward and upward. The tangential speed decreases with increasing distance from the blade. Approximately one-third to one-half of the circumferential distance to the upstream blade, particles move in an outward and downward direction. The result is a weak vortex in the horizontal plane with a circulation oriented in the direction opposite to the blade rotation. In addition to this horizontal re-circulation component, there is a stronger vortex in the vertical plane with particles moving up at the blades and down the free surface of the heap. In the region immediately downstream of a blade, particles move radially outward and downward to fill the trailing wake (Conway et al., 2005; Lekhal et al., 2006). The free surface layers avalanche down the surface, but also have an inward velocity component since the heaps are tallest near the perimeter of the cylinder (Conway et al., 2005; Lekhal et al., 2006), although Stewart et al. (2001b) reported that particles avalanche radially outward on the free surface. Particles can remain in this vortex for a considerable time period. Stewart et al. (2001a) also observed that particles could remain trapped in the vortex in their experiments for up to 60 blade passes. Particles in the region between the blade tips and the wall typically have small velocities (Conway et al., 2005). Local particle velocities within the bed appear to be normally distributed (Stewart et al., 2001b) while the surface speeds scale linearly with the impeller speed, except for the wake region immediately downstream of the blade where gravity governs the particle speed (Stewart et al., 2001a).

2.2. Influence of bed depth

The depth of the particle bed also has a significant impact on particle motion. Stewart et al. (2001a) used positron emission particle tracking (PEPT) to investigate bed motion over a range of bed depths ($H/d=7.3$–36, where H is the level bed depth and d is the particle diameter) and relatively slow impeller speeds (10–160 rpm, corresponding to Froude numbers between 0.014 and 3.56, where the Froude number is defined as $R\omega^2/g$, where R is the radius of the blade, ω is the blade rotational speed, and g is the acceleration due to gravity). The height and width of this heap as well as the re-circulation strength, especially in the radial direction, diminish as the bed depth increases. At shallow bed depths, most of the material in the mixer moves with the impeller blades while for deeper beds a greater percentage of the bed moves more slowly than the blades. Stewart et al. (2001a) also reported that increasing bed depth results in a broader axial velocity component distribution, but narrower radial and circumferential velocity distributions.

2.3. Influence of blade angle

Several studies have examined the influence of the angle of the flat blades used in many mixers. From DEM simulations, Chandratilleke et al. (2009) found that for a bed in the heaping regime, re-circulation strength, mixing rate, heap height, and the degree of bed deformation are largest for a blade angle that is perpendicular to the mixer base (i.e., 90° from the upstream horizontal). The 90° blade also results in a narrower particle speed distribution with a larger mean particle speed

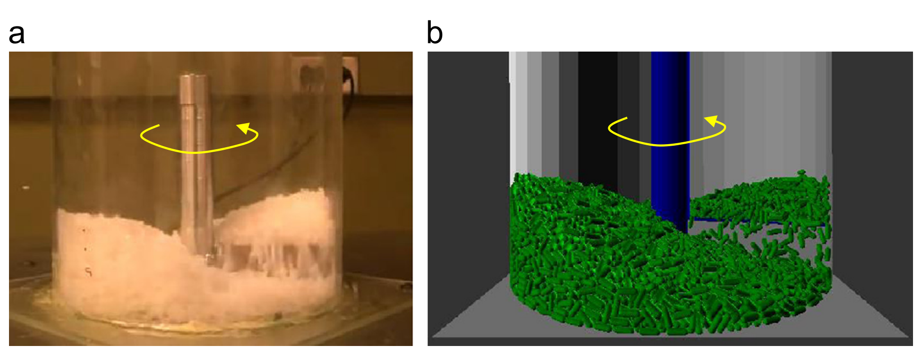

Fig. 1. (a) A photograph of a bed exhibiting the heaping behavior. (b) A snapshot from a DEM simulation with particles having an aspect ratio of $AR=3$. The initial dimensionless bed depth is $H/H_B=1.0$.

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