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Dynamics of non-spherical particles in a rotating drum

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HIGHLIGHTS

- The RPT technique is used to follow large non-spherical particles in a rotating drum
- A model to predict the particle residence time along streamlines is developed
- The mixing of different shaped particles can lead to unexpected core segregation patterns
- The effect of the particle shape on mixing and segregation is highlighted
- A higher degree of preferred spatial orientation leads to a smaller axial dispersion coefficient

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ABSTRACT

Considerable amount of experimental work has been performed to elucidate the behavior of granular flow inside a rotating drum and it has yet to be clearly understood. However, a majority of these investigations have involved spherical or nearly spherical particles. The extent of the experiments involving non-spherical particles previously carried out was limited by the experimental technique used for the investigation or the inability to single out the effect of the particle shape. In this work, the radioactive particle tracking technique (RPT) is adapted to follow large non-spherical particles inside a rotating drum. The particles consist of pharmaceutical tablets containing a suitable compound, thus enabling their use as a tracer particle. Three crucial aspects of particle dynamics inside a rotating drum are studied: residence time in the active and passive layers, mixing and segregation, as well as axial dispersion. The results obtained for non-spherical particles are compared to those which would be predicted using models developed for spherical of nearly spherical particles. For the different shapes studied in this work, it is found that particles having an aspect ratio greater than two can lead to significant deviations in velocity profile and residence time. In addition, the mixing of different shaped particles is observed to lead to unexpected core segregation patterns. Lastly, it is found that the non-spherical particle higher degree of spatial orientation in the active layer leads to a lower axial dispersion coefficient than the ones obtained with spherical particles.

1. Introduction

Rotating drums are widely used to process granular materials in a great variety of industries such as pharmaceutical, food processing, polymer, ceramic, chemical, metallurgical, solid waste treatment, etc. Due to their adequate mixing and heat transfer efficiency (Descoins et al., 2005) as well as their ability to handle heterogeneous feedstock (Boateng, 1998), they are used in a broad range of processes which involves, for example, size reduction, sintering, mixing, drying, heating, cooling, chemical reactions or solid thermal decomposition (e.g. incineration, pyrolysis, combustion) operations. Heat and mass transfer, determined by solid transport and particulate mixing, control and/or limit these operations (Heydenrych et al., 2002; Liu et al., 2006; Mellmann et al., 2004). The rotating drums are usually operated in the so-called rolling regime since it provides superior particle mixing, resulting in enhanced heat transfer (Fantozzi et al., 2007; Li et al., 2002; Liu et al., 2006). This regime is characterized by two regions: a passive layer found near the cylinder wall, where particles move as a solid body, and an active layer, where the particles avalanche and cascade downward. It is widely accepted that mixing, segregation, heat transfer or other transport phenomena mainly occur in the active layer (Cheng et al., 2011; Ding et al., 2001; Ingram et al., 2005; Liu and Specht, 2010; Liu et al., 2006). Understanding the phenomena occurring inside rotating drums on a fundamental level is essential for optimal design and operation of this equipment (Heydenrych et al., 2002; Khakhar et al., 1997b; Mellmann, 2001). In particular, characterizing the transverse flow of

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particles is of primary importance. Although rotating drums represent a relatively simple geometry, the granular flow occurring inside them is rather complex (Boateng, 1998; Ding et al., 2002a; Ndiaye et al., 2010). If the particles are reagents and/or change size or shape over the course of the process, like in incineration, pyrolysis, sintering, combustion or size reduction operations, the problem becomes much more complex as new phenomena affecting the particle dynamics may occur.

Experimental studies of granular flow are tedious mainly because of the opaque nature of such materials. Nevertheless, a considerable amount of experimental work has been performed in order to elucidate the behavior of granular flow inside a rotating drum. To perform these investigations, a wide selection of experimental techniques, such as in situ bed freeze (Wightman and Muzzio, 1998), magnetic resonance imaging (MRI) (Kawaguchi, 2010; Nakagawa et al., 1993; Hill et al., 1997), fiber optics probe (Boateng and Barr, 1997), positron emission particle tracking (PEPT) (Ding et al., 2001; Ingram et al., 2005; Parker et al., 1997), particle image velocimetry (PIV) and particle tracking velocimetry (PTV) (Alexander et al., 2002; Felix et al., 2002, 2007; Jain et al., 2002, 2004; Mellmann et al., 2004; Thomas 2000) and radioactive particle tracking (RPT) (Alizadeh et al., 2013a; Sheritt et al., 2003), have been used. However, a majority of these investigations have involved spherical or nearly spherical particles. As it was previously mentioned, one advantage of rotating drums is their ability to handle varied feedstock, i.e. granular material having a wide distribution of size, density, shape, roughness or else. It has been known for quite some time now that the particle shape affects the dynamical properties (Ridgway and Rupp, 1971). The behavior of non-spherical particles differs from that of spherical particles in terms of their compaction efficiency, resistance to shear, dilation under shear, transfer of momentum between translational and angular motions as well as their ability to form arches and block the flow (Cleary, 2010). Experimental investigations of granular flow in rotating drums involving non-spherical particles drums are rather limited: Boateng and Barr (1997) used limestone and rice grains, Van Puyvelde et al., (2000) used shale, Woodle and Munro (1993) used particles made from and with ovoid, shell and tube shapes, Henein et al., (1983, 1985) used sand, limestone and gravel, and Ingram et al., (2005) used sand. In the pharmaceutical field, the dynamics of non-spherical particles is particularly of interest for particle and tablet coating applications, which are generally conveyed in a pan coater consisting of a rotating drum. Wilson and Crossman (1997) as well as Tobiska and Kleinebudde (2003) studied the effect of the tablet shape and size on the tablet film coating uniformity and efficiency. While useful, the results and extent of these studies involving non-spherical particles were restricted by either the experimental technique used, the inability to single out the effect of the particle shape or the objectives of the study.

This work aims at investigating three crucial aspects of the particle dynamic inside a rotating drum containing non-spherical particles: the residence time in the active and passive layers, the mixing and segregation of these particles, and the axial dispersion. To do so, the radioactive particle tracking (RPT) technique was adapted to follow the motion of non-spherical particles, which are in fact non-spherical tablets suitably built to become radioactive tracer particles. The results obtained for the non-spherical particles are compared to models previously developed for spherical or nearly spherical particles.

2. Methodology

As previously mentioned, numerous non-intrusive experimental techniques have been used to study granular flow. In particular, PIV and/or PTV can solely provide information on flow at the bed surface or, if the rotating drum has a transparent side, flow under the surface. In the latter case, the flow measured is affected by the presence of the end wall as well as the material constituting it, and may not represent what is going on inside the particle bed. Using PIV and/or PTV is then limited to two-dimensional systems and properties like axial dispersion can hardly be quantified. MRI and PEPT can also be used though they present limitations on the size and constitution of the system that can be studied, not to mention they are also expensive. On the other hand, RPT does not present any limitations on the system size and is much cheaper than these two methods. However, its extension to a system having irregular moving boundaries is not trivial (Doucet et al., 2008). This technique was used to carry out the investigations of this work since the rotating drum possesses simple moving boundaries. The next section briefly describes the RPT technique and the adaptations performed to apply it to this work.

2.1. RPT

RPT is a non-invasive experimental velocimetry and tomography technique that can be used to study the flow dynamics inside a variety of systems. In this technique, the trajectory of a single tracer particle emitting isotropic γ-rays can be reconstructed using a phenomelogical model relating the number of γ-rays received and effectively counted by an array of scintillation detectors strategically placed around the system. Assuming a nonparalyzable counting RPT setup, the phenomenological relation linking the number of γ-rays C counted by a scintillation detector to the position $\vec{r}$ of the tracer particle is given by:

$$C(\vec{r}) = \frac{T\nu A\phi\zeta(\vec{r})}{1+\tau\nu A\phi\zeta(\vec{r})} \tag{1}$$

where $T$is the sampling period (s), ν the number of distinct energy γ-rays emitted by the source, A the activity of the source (Bq), τ the detector dead-time (s), ζ the detector absolute efficiency and ϕ the fraction of the energy spectrum captured by the detector. ζ is rigorously evaluated using a Monte Carlo technique developed by Beam et al., (1978). Following a calibration procedure, Eq. (1) is used to compute the detector count dictionaries, corresponding to theoretical count rates associated with specific positions inside the system.

In this study, the detectors were positioned according to guidelines coming from an optimization strategy to find an optimal configuration for detectors given specific experimental conditions, as developed by Dubé et al., submitted for publication. Further details on the traditional application of the RPT technique can be found in Larachi et al., (1994), Roy et al., (2002) and Dubé et al., submitted for publication.

Similar to Alizadeh et al., (2013a), this work uses a tracer particle containing the isotope ^{24}Na. This isotope emits two γ-rays at energy levels of 1.368 and 2.754 MeV, and has a relatively short half-life (14.95 h). Explanations on why this particular isotope is used are provided in Section 2.2.1. To account for the short half-life, Alizadeh et al., (2013a) suggested using a second tracer particle having the same activity as the first tracer particle, placed outside of the vessel, to monitor the source loss of activity throughout experiments. This method yielded satisfactory results when the tracer particle consisted of a 3–6 mm radius glass bead. However, since the count dictionaries with this strategy are corrected according to count values obtained from an emitting sentinel having a different specific absolute efficiency because it does not take into account the particle bed, the error in the tracer particle trajectory reconstruction increases with the experimental time. In this work, the decrease in activity is instead accounted for