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Axial segregation of a binary mixture in a rotating tumbler with non-spherical particles: Experiments and DEM model validation

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ABSTRACT

The axial segregation behavior of a binary mixture made of spherical and non-spherical particles is studied experimentally and numerically using Discrete Element Methods (DEM). Two different shape approximations are used for modeling cylindrical particles: the equivalent sphere and the multisphere approximation. The coefficients required by DEM are calibrated partly by separate experiments, partly by geometrical considerations. The main objective is to dispose of a simple procedure to characterize the friction coefficients and to evaluate the main changes imposed by shape in an axial segregated rotating tumbler. The simulations match with the experimental observations in the multisphere case, the transient behavior is caught with accuracy with both approximations.

1. Introduction

Some commercially important issues in granular media concern the optimization of their transport, storage or mixing properties. In fact, most of the energy in these industries is dissipated by the Joule effect during granular materials mixing. Rotating tumblers are simple devices, they find application in many fields of industry and are used for many purposes [1–5]; however, their efficiency is often impaired by several operational problems, like segregation. These processes are usually designed from empirical knowledge. The lack of meaningful and robust correlations between the characteristics of the powders and their behavior during mixing storage is critical for the design of industrial solutions. Optimized solutions based on energy savings could be obtained with a better understanding of the property-structure link from the (micro-) scale of the particle to the (macro-) scale of the process. Segregation affects many devices for the treatment of granular material, it is often driven by differences in particle properties, and it is affected by the tumbler geometry. There are two kinds of phenomena: radial segregation, a fast segregation phenomenon in which particles segregate forming a radial core inside the solid bed, and axial segregation.

Axial segregation is a meta-stable slow segregation phenomenon that consists in the separation of particles in bands approximately perpendicular to the axis, it is initiated on the end walls [6–8], with bands traveling inside the rotating tumbler and merging [9]. The origin of the formation of such bands is the initial creation of a segregated core of grains which is formed in the radial direction of the drum [10–12]. Understanding this initial radial segregation is a key factor in achieving a better understanding of the complete segregation process.

Both radial and axial segregations in rotating drums occur, for example, when particles differ in density, frictional properties or size. Most studies up to date on the segregation of a granular mixture in rotating cylinders have only considered spherical particle [13]. A challenging case is that in which particles of different shape and density are present. This last situation is of practical importance since many of the granular flows encountered in nature and industry involve particles of different sizes, shapes, and densities. Recently, some work reported the formation of a streak pattern in a mixture of spherical and non-spherical particles in rotating tumblers [14], suggesting that the percolation mechanism during segregation is hampered by the effect of particle shape [15,16].

In order to improve our understanding, numerical 3D modeling is of paramount importance. One way for doing this is the Discrete Element Method (DEM) [17], a technique that tracks a large assembly of particles using a Lagrangian approach, resolving for each particle the Newton equations of motion and evaluating the forces during contact through a soft-sphere approach. DEM gives detailed information on every particle inside the simulation environment, but it is often difficult to model non-spherical particles. Different methods exist to represent shape [18–25] in the DEM framework, but most methods are not versatile and lack generality. The multisphere approximation can overcome this problem, it consists of clustering multiple spheres together in order to approximate the desired shape, however high quality approximations

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Nomenclature

b	Momentum arm
Cs	Mean number of wood pellets per unit length
$C_s(z)$	Number of wood pellets per unit length as a function of the axial direction
e	Eccentricity
$\langle \mathbf{e} \rangle$	Mean eccentricity
E	Young's modulus
F	Force
I_x, I_y, I_z	Moment of inertia
k	Axial coordinate parameter
l	Length of the pellets
L	Length of the tumbler
M_μ	Frictional torque
N^a	Steel particles in a band
$N^a{}_{tot}$	Total Steel particles
N.R.	Number of rotations
n	Normal direction
r	Radius of a particle
r_c	Radius of the cylindrical particle
r_e	Equivalent sphere radius
R	Tumbler radius
t	Tangential direction
u	Unit vector

Greek letters

$\Delta^{seg}(t)$	Segregation degree
Δt	Collision time
Δz	Length of a mesh element
ε	Coefficient of restitution
θ	Poisson ratio
μ	Sliding friction coefficient
μ_r	Rolling friction coefficient
ρ	Density
ψ	Sphericity
ω	Tumbler rotation speed

Subscripts

t	Tangential direction
n	Normal direction
p	Wood pellet
r	Radial direction
z	Axial direction
s	Steel
w	Wall

may require a high number of spheres and increase considerably the load on the simulation [26].

In this work, an experimental analysis of axial segregation on a laboratory-scale rotating tumbler for a mix of wood pellets and steel spheres is presented. The choice of these particular materials is principally due to the experimental problem of the SEA Marconi pyrolysis reactor, illustrated in a previous publication [26]. Experimental measurements are compared with DEM simulations. The wood pellets were simulated through two different approaches, the multisphere method, and the equivalent sphere approximation, consisting of a sphere representation of the real particle inside the simulation environment. Two crucial aspects of particle dynamics inside the rotating drum are studied: mixing and radial segregation, as well as axial dispersion. Both experimental and numerical results are consistent with the existence of fast density-driven axial segregation behavior with the wood particles on the end walls and steel spheres concentrating in the central part of the cylinder.

2. Experimental setup

The experimental system used in this work is presented in Fig. 1. The rotating tumbler (Fig. 1, element 1) has a diameter of 0.12 m and it is 0.135 m long, the tumbler walls are all transparent for visual observation. The system is closed to the solid particles.

A CCD high-speed camera allows the recording of images through the walls; a speed of 15 frames per second was used for tests with steel balls and pellets mixed together. Three different views were used to record different zones of the rotating tumbler: the cylinder walls before the avalanche (Fig. 1, element 2a), the radial zone on the end walls (Fig. 1, element 2b) and the surface of the bed (Fig. 1, element 2c). The frames are analyzed afterwards to study the segregation regimes and the dynamic angle of repose through thresholding of the images. The rotating tumbler is connected to an electric engine, which allows a precise rotation with no oscillation of speed and no vibrations for a rotation velocity in the range of [10 rpm, 100 rpm]. The whole system is mounted on an adjustable support, to assure the horizontality of the rotating tumbler. This system was used for calibration purposes as well as for segregation studies. Two types of particles were used in the experiments: steel spheres and wood pellets (Fig. 2).

The measured properties are presented in Table 1; the length distribution of wood pellets is presented in Fig. 3. The wood pellets are considered as cylindrical; their diameter distribution is very narrow and considered constant (6 mm) in this work.

3. Simulation methods

The simulations presented in this work are based on the model developed by Cundall and Strack [17], namely the DEM (Discrete Element Method); it consists in a Lagrangian tracking of every particle in the simulation, contact is modeled trough the soft-sphere approach, i.e. particles are allowed to slightly overlap in order to compute the forces

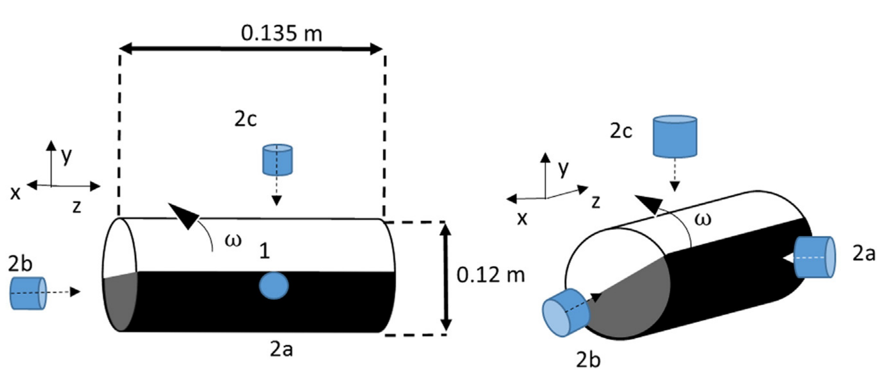

Fig. 1. Experimental apparatus. 1 Rotating tumbler, 2a Camera position back view, 2b Camera position radial view, 2c Camera position axial view.