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Impact of granular segregation on the solid residence time and active-passive exchange in a rotating drum

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HIGHLIGHTS

- Granular segregation of a binary-size mixture studied via DEM.
- Effect of segregation on residence time and active-passive interchange studied.
- Solid exchange rate between the two regions greater for the small particles.
- The exchange rate for both the particle types proven to be global parameters.
- Rotating speed exerts a greater influence than particle diameter ratio.

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ABSTRACT

Via the discrete element method, a three-dimensional partially filled rotating drum operating in the rolling regime is numerically simulated to investigate the solid residence and inter-region exchange behaviors in the active and passive regions, and their dependence on the operating parameters of rotating speed and particle diameter ratio of the binary-size mixture. The results demonstrate the effects of size-segregation of the binary-size mixture: (i) for both particle displacement and residence time, the magnitude of large particles are greater, and the magnitudes in the passive region are greater than that in the active region; (ii) the solid exchange rate between the two regions is greater for the small particles; (iii) although the solid exchange rate of each particle type evolves with time due to the evolving size segregation, the exchanging rate between the active and passive regions is proven to be global parameter, which is not influenced by size-segregation; (iv) changes in the rotating speed has a greater influence than that in particle diameter ratio in the ranges investigated. Collectively, these results shed more light on the impact of size segregation of a binary-size mixture on the characteristics of the rotating drum.

1. Introduction

The rotating drum is frequently adopted to study granular flow behavior due to its simple geometry and also the ability to process particles in many industries (e.g., chemical, pharmaceutical) due to the wide-ranging flow characteristics; therefore, it is necessary to have an in-depth understanding of the inherent behaviors from both the academic and industrial perspectives (Ottino and Khakhar, 2000). Six behaviors of the particles are well acknowledged, namely, sliding, avalanching, rolling, cascading, cataracting, and centrifuging (Mellmann, 2001). For the ubiquitous polydisperse systems (i.e., particles of different particle diameters and/or densities), segregation of the various particle types is inevitable (Ottino and Khakhar, 2000). As the segregation impacts the product quality significantly, typical solutions in practical operations to combat segregation can fall into two categories (namely, change the particles or process operation/design) (Ottino and Lueptow, 2008) to enhance the mixing in the system, such as cohesive manipulation (Li and McCarthy, 2003), the choice of particle density and size (Jain et al., 2005a), the addition of baffles or blades (Jiang et al., 2011; Vargas et al., 2008; Yu et al., 2015), the exploration of optimum operating conditions (Arntz et al., 2008). Therefore, an in-depth understanding of the segregation behavior of granular flow can help to optimize these kinds of processes and has been sought over the past few decades.

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Nomenclature

d_p	particle diameter, m
e	restitution coefficient, dimensionless
$\boldsymbol{F}_c$	contact force, N
$\boldsymbol{F}_{cn}$	normal contact force, N
$\boldsymbol{F}_{ct}$	tangential contact force, N
$\boldsymbol{g}$	gravitational acceleration, m/s^2
G	shear modulus of solid phase, Pa
G^*	equivalent shear modulus of solid phase, Pa
I	particle moment of inertia, kg·m^2
k	total number of particles or walls colliding with current particle, dimensionless
$k_{n,ij}$	normal stiffness coefficient of solid phase, N/m
$k_{t,ij}$	tangential stiffness coefficient of solid phase, N/m
m	particle mass, kg
$\boldsymbol{M}$	torque exerted on a particle, N·m
m^*	equivalent mass of a particle, kg
$\boldsymbol{n}$	normal unit vector between colliding particles, dimensionless
R	particle radius, m
R^*	equivalent radius of a particle, m
S_n	normal stiffness, N/m
S_t	tangential stiffness, N/m
t	time instant, s
$\boldsymbol{t}$	tangential unit vector between colliding particles, dimensionless
$\boldsymbol{U}_s$	particle velocity, m/s
$\boldsymbol{v}_{n,ij}$	normal component of relative velocity between colliding pair, m/s
$\boldsymbol{v}_{t,ij}$	tangential component of relative velocity between colliding pair, m/s
$\boldsymbol{v}_p$	particle velocity, m/s
Y_p, Y^*	actual and equivalent Young's modulus, Pa
Z	half-length of drum axial length, m

Greek symbols

β	damping ratio, dimensionless
$\delta_{n,ij}$	normal displacement between particle i and particle j, m
$\delta_{t,ij}$	tangential displacement between particle i and particle j, m
μ	friction coefficient between particles or particle-wall, dimensionless
ψ	exchanging rate of a specific particle time between the two regions, kg/s
$\boldsymbol{\omega}$	particle angular velocity, °/s
γ_n	damping coefficient in normal direction, kg/s
γ_t	damping coefficient in tangential direction, kg/s
ν	Poisson ratio of solid phase, dimensionless

Subscripts

c	contact force
i	particle i
j	particle j
n	normal component of a variable
t	tangential component of a variable

Abbreviations

3-D	three-dimensional
DEM	discrete element method
SRT	solid residence time
TFM	two-fluid model

Experimental studies on the segregation behavior in a rotating drum has been extensive reported, such as, radial segregation (Khakhar et al., 1997; Pereira and Cleary, 2013), axial segregation (Alizadeh et al., 2013; Nakagawa, 1994; Windows-Yule et al., 2016), evolution and scaling of the segregation patterns (Choo et al., 1997; Zuriguel et al., 2009), effect of a non-cylindrical drum geometry (Jain et al., 2005b), flowing layer thickness (Félix et al., 2002), diffusivity (Ding et al., 2002a, 2002b), dispersion (Alizadeh et al., 2013) and coarsening (Tilo, 2015). It has been shown that (i) for multi-component size systems a high purity inner core of smallest particles surrounded by the less pure region of intermediate particles and an outermost corona of largest particles (Pereira and Cleary, 2013); (ii) the extent of segregation increases with the dimensionless segregation velocity and dimensionless diffusivity (Khakhar et al., 1997); (iii) the initial segregation pattern evolves with time (Hill et al., 1997); (iv) the traveling axial segregation patterns are bi-directional (Choo et al., 1997); (v) streaks of small particles are formed within regions of large ones and the number of streaks is fixed over a range of drum rotation rate (Jain et al., 2005b); (vi) the velocity profile and active layer thickness are similar for both monodisperse and polydisperse systems (Alizadeh et al., 2013); (vii) the unidirectional flow between the axial segregation bands is driven by the small differences in size of the small particles at the band edges (Tilo, 2015); and (viii) the axial segregation cannot be explained by a single mechanism (Windows-Yule et al., 2016).

Numerical simulation of the dense granular flow has been carried out in parallel with the experimental studies. In general, the two-fluid model (TFM) (Gidaspow, 1994) and discrete element method (DEM) (Capecelatro et al., 2015; Guo and Curtis, 2015; Kumar et al., 2015; Sakai et al., 2015; Shigeto and Sakai, 2011) are the two main approaches used to simulate the particle flow at the scale of computational cell level and the scale of the individual particles, respectively. For the dense granular flow in the rotating drum, because of the limited resolution, reports on using TFM are rare (He et al., 2007; Santos et al., 2016). The DEM is more popularly employed because of the advantage of obtaining the detailed particle-scale characteristics at each time step, for examples, the competition between mixing and segregation (Dury and Ristow, 1999), radial and axial segregation (Pereira and Cleary, 2013), coarsening and oscillating behavior of the axial segregation band (Taberlet et al., 2006), three-component segregation (Rapaport, 2007), onset mechanism for axial band formation (Chen et al., 2010), flow regime and various forms of radial segregation (Arntz et al., 2008), and axial dispersion (Alizadeh et al., 2014; Third et al., 2011). Through these numerical studies, interesting insights on the segregation mechanisms have been obtained. The following tips are several examples. The coarsening and oscillatory motion of axial bands involves flow of small particles through the radial core in the rotating drum (Taberlet et al., 2006). Regarding three-component granular segregation, the medium-sized particles tend to be located between alternating bands of small and large particles (Rapaport, 2007). For radial segregation, the percolation mechanism may provide a qualitative explanation for the distinctive segregation behavior in the rotating drum (Arntz et al., 2008). As for axial segregation, the end walls initiate the axial band formation via an axial flow due to friction caused by the end walls (Chen et al., 2010), and a small axial flow between segregated