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A design heuristic for optimizing segregation avoidance practices in horizontal drum mixers

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ABSTRACT

Segregation is a major problem for many solid processing industries. Differences in particle size or density lead to flow-induced segregation within the surface layer. Here we examine methods of avoiding radial segregation in a horizontal drum mixer. Recently, it has been suggested that segregation in this type of particle mixer can be thwarted if the sheared (surface) regions of the bed are inverted at a rate above some critical frequency. Further, it has been hypothesized that the effectiveness of this technique can be linked to the probability distribution of the number of surface layer "passes" a particle takes per rotation of the drum. In this article, various baffle configurations are numerically and experimentally studied to investigate the efficacy of this measure as a design heuristic for the development of improved drum mixing devices. We choose the horizontal drum geometry as it represents the simplest possible example of a tumbler-type mixer, however, we expect the results found here regarding the efficacy of our design heuristic to be generic for any surface-dominated mixing device.

1. Introduction

Granular materials are ubiquitous and it is hard to find a process industry which does not handle granular materials in some form. These materials are widely used in chemical, pharmaceutical, cement, food, construction and metallurgical industries. Mixing, heating and granulation of particulate materials are just a few of the many examples where a rotating drum or tumbler is used to achieve a desired objective. However, when a mixture of two different types of particles is tumbled in a rotating cylinder (a so called solid mixer) they tend to segregate or de-mix. This undesired phenomenon causes problems in maintaining uniform product quality and results in revenue losses across many industries.

The flow behavior in a rotating cylinder can be complex and it is well established that mixing and segregation patterns are sensitive to the container geometry and fill level [1–3]. Henein and others [4,5] have identified multiple regimes of flow with increasing cylinder speed of rotation: slipping, avalanching, rolling, cascading and centrifuging. In industrial applications, rotating cylinders are typically operated in the rolling flow regimes. In the rolling regime, a thin layer of particles moves at high velocity in the free surface (called the shear or "surface" layer), whereas the rest of the bed rotates as a solid body (called the passive layer or static bed) [6]. In a half-filled tumbler with circular cross-section, the mixing and segregation of particles occur only in the shear layer and, therefore, it is the shearing layer that needs particular attention if something is to be done to thwart segregation.

One can observe that past studies that proposed solutions to combat segregation can be categorized into two groups, both of which are generally devised on an ad-hoc basis, and include: change the particles or change the process [7]. Samadani and Kudrolli [8] found that segregation could be reduced by adding a small volume fraction of fluid to a mixture of small and large glass beads. Li and McCarthy [9] found that segregation could be turned off or *on* by adding small amounts of moisture when using particles of various types, multiple sizes, and different surface characteristics. Hajra and Khakhar [10] showed that segregation could be eliminated by using a small (in comparison to the diameter of the cylinder) rotating impeller placed at the axis of rotation, that is, in the surface layer. Jain [11] and Thomas [12] performed experiments for binary mixtures composed of different sizes and different density particles and they found that mixing can occur instead of segregation if the denser beads are bigger (as the segregation tendencies will cancel), and also if the ratio of particle size is greater than the ratio of particle density.

Recently, a more theory-based study by Shi et al. [13] has shown that periodic flow inversions via selective baffle placement – in a tumbler-type mixer – can serve as a generic method for eliminating segregation regardless of particle properties. Beyond the work of Shi et al. [13], we find that very little is known from a theoretical point of view on the effect of baffles on solid mixing, even in simple cases limited to mono-dispersed systems [1,14].

In this paper, we use experiments and simulations to study the effects of various baffle designs and operating parameters on mixing

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of binary mixtures with different sizes or densities. We confirm that periodic flow inversion can be used to reduce segregation in a rotating cylinder and explore different baffle shapes and placements that are engineered based on Shi et al.'s [13] hypothesis of flow modulation. Attempts are made to link this technique to the probability distribution of the number of times a particle passes through the surface layer per rotation of the drum. Using this information, predictions are made as to which baffle configurations would produce better mixing, so that we might use this criterion as a design heuristic for screening future mixer geometries.

2. The hypothesis: time modulation and layer pass analysis

Time-modulation in fluid mixing and other dynamical systems [15] is a fairly common practice, but has found only limited applications in granular processing [1,16,17]. As already mentioned in the Introduction section, Shi et al. [13] have shown that periodic flow inversions via selective baffle placement can serve as a generic method to thwart segregation. The key to adapting this idea to free-surface segregation lies in recognizing two important facts: that it takes a finite time for material to segregate and that there is always a preferred direction that particles tend to segregate. For example, in a free-surface flow, small particles need time to percolate through the flowing layer; thus, if the flow is interrupted before the small particles reach the bottom of the flowing layer, segregation can be prevented. This relatively simple observation can be employed to engineer systems that counteract segregation.

In order to capitalize on the fact that this flow interruption can thwart segregation, one next needs to invert the flowing layer, prior to reinitiating the flow (and the segregation). One way to achieve this two-step process in a continuous flow is to invert the flowing layer at a sufficiently high frequency, f, $f > t_s^{-1}$, where t_s is the characteristic segregation time. A critical issue with this technique is that a full understanding of segregation kinetics – and therefore, the characteristic segregation time, t_s – is still lacking. However, this hypothesis can be tested *indirectly* for many baffle configurations in a rotating cylinder by examining the probability distribution of the number of surface layer passes a particle takes per rotation of the drum, as described below.

Consider an unbaffled, half-filled tumbler with circular cross section. In this geometry, one observes that the flow is composed of: first, a pass through the sheared/surface layer, then a pass through the static portion of the bed, and so on. It is important to note that the static portion of the bed in a rotating drum simply "stores" the material and returns it (after a full 180-degree change in orientation) for its next pass through the surface layer. Moreover, in an unbaffled tumbler, the surface layer itself also induces a 180-degree orientation change (due to the almost-linear shear profile within this layer). Thus, for a full rotation the effect of the static bed and surface layer on the segregation orientation cancels each other and *a particle will return to the segregating region (the surface layer) always in the same orientation in which it left*. If one were to quantify this orientation cancelation process, we could argue that matching a single surface layer pass to a single static bed pass is the worst-case scenario for segregation. In contrast, if the frequency of surface layer passes and static bed passes is decoupled, the orientation of segregation (for a tracer particle) would seemingly change for each iteration through the surface layer.

Now if we place a baffle near the axis of rotation (thus, near to the shearing layer), we periodically alter the flowing layer so that we achieve both (i) a smaller average uninterrupted flow length, L, and (ii) significant variation in the time between layer passes. The fact that the static bed and the flowing layer(s) no longer produce related orientations is key to the results reported here. In order to test this hypothesis, the numerical tool DEM (Discrete Element Method) is used in the present study. The details of this technique along with its application to the present problem will be elaborated in the subsequent sections.

3. Modeling: Discrete Element Method (DEM)

The Discrete Element Method (DEM) is also known as Particle Dynamics (PD) [18] where the trajectory of each and every particle is tracked via simultaneous integration of the interaction forces between individual pairs of particles [19,20]. While these forces typically include only contact forces – normal (Hertzian) repulsion and tangential (Mindlin) friction, see Ref. [21] – and gravity, additional particle interaction forces (such as surface adhesion [22,23] and van der Waals [24]) can be easily incorporated. In particular, this technique has been quite successful in simulating ensembles of granular materials, yielding insight into such diverse phenomena as force transmission [25], packing [26], wave propagation [27], agglomeration formation and breakage [22], cohesive mixing [28], bubble formation in fluidized beds [29], and segregation of free-flowing materials [30].

In a granular flow, the particles experience forces due to interactions between particles (e.g., collisions, contacts, or cohesive interactions) as well as interactions between the system and the particles (e.g., gravitational forces). In this work, the collisional forces are modeled after the work of Hertz and Mindlin [21]. A thorough description of the interaction laws from contact mechanics (collision forces) can be found in elsewhere [23,31,32]; therefore, they will not be reviewed here. Typically, a numerical experiment consists of a mono-disperse/bi-disperse system of perfectly smooth spheres bounded by a wall of immobile particles with periodic boundaries in the longitudinal z direction. The number of particles is determined by the fill level and the particle diameters. The wall of the drum is rotated at a constant angular velocity, ω. A typical initial condition for the rotating tumbler simulations is obtained by allowing a bed of particles, arranged in a randomly perturbed lattice, to settle under the action of gravity. From this initial configuration, a prescribed angular velocity is imposed and the simulation is allowed to proceed for approximately 20 revolutions based on the rotation rate prescribed. Then, the Intensity of Segregation (Eq. (1)), as defined in the next section, is determined as a function of time in order to measure the mixing (or lack thereof).

Our experiments use cellulose acetate particles, however, in many of our simulations, the particle stiffness and other parameters used are reduced in order to decrease the required simulation time (using so-called "soft" particles; a practice shown to have essentially no impact on flow kinematics [20]). Table 1 lists the material properties used in the simulations. We should note that, when directly comparing simulation results with the experimental data, we use an elasto-plastic model with actual material properties (for cellulose acetate). On the other hand, "soft" material properties are used for performing other studies (e.g., effect of number of baffles) when comparison with experimental data is not the primary aim, as simply capturing correct kinematics should be sufficient in these cases.

4. Experiment

Experiments are carried out in a quasi 2D rotating cylinder (1.5 cm in length and 13.8 cm in diameter), which is mounted on a circular plate attached to a bigger rotating drum. The bigger drum is rotated using a computer controlled stepper motor at a fixed rate (6 RPM). The cylinder is made up of two sets of transparent glass disks, that are fitted face-to-face to close the cylinder. This arrangement also helps in dispensing

Table 1
Material properties used in the simulations.

Parameter	Value
Young's modulus (E, GPa)	1.5 (acetate), 0.03 (soft)
Density (p, kg/m^3)	1300 (acetate), 1000 (soft)
Coefficient of friction (μ)	0.30
Poisson ratio (v)	0.43 (acetate), 0.33 (soft)
Yield stress (σ_y, MPa)	30.0 (acetate), 0.3 (soft)