Analysis of radial segregation of granular mixtures in a rotating drum

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Abstract. This paper considers the segregation of a granular mixture in a rotating drum. Extending a recent kinematic model for grain transport on sandpile surfaces to the case of rotating drums, an analysis is presented for radial segregation in the rolling regime, where a thin layer is avalanching down while the rest of the material follows rigid body rotation. We argue that segregation is driven not just by differences in the angle of repose of the species, as has been assumed in earlier investigations, but also by differences in the size and surface properties of the grains. The cases of grains differing only in size (slightly or widely) and only in surface properties are considered, and the predictions are in qualitative agreement with observations. The model yields results inconsistent with the assumptions for more general cases, and we speculate on how this may be corrected.

PACS. 47.55.Kf Multiphase and particle-laden flows – 83.70.Fn Granular solids

1 Introduction

The production of many goods, ranging from pharmaceuticals and foods to polymers and semiconductors, depends on reliable uniform mixing of granular materials. Although there have been several recent advances, particulate mixing is poorly understood, and one cannot a priori predict the effectiveness of any mixing process. Indeed, mixing operations often result in segregation or de-mixing, and even the parameters that control mixing and segregation are not fully understood.

Rotating drums, or kilns, are employed in industry to carry out a range of operations; some examples are the calcination of limestone, reduction of oxide ore, clinkering of cementitious materials, waste incineration and calcination of petroleum coke. Owing to its industrial importance the rotary kiln has been the subject of numerous investigations. Significant improvement in kiln performance may be achieved by better understanding grain transport during operation.

In a rotating drum several regimes of bed motion have been identified, namely, slipping, slumping, rolling, cascading, cataacting and centrifuging [1]. The most desirable bed motion for many industrial operations is the rolling mode, as it helps in promoting good mixing of the particles along with rapid renewal of the exposed material. The rolling regime is characterized by two distinct regions: the “active” and “passive” layers [2]. Grains in the passive layer execute rigid body rotation along with the drum and the streamlines are circular (see Fig. 1). The active layer is usually very thin in comparison with the passive layer.

While rotating drums are used to mix particles of varying sizes and shapes to obtain a homogeneous mixture necessary for certain industrial processes, there is consider-
able evidence of segregation when the charge is a granular mixture of different properties. A mixture of grains differing either in size and/or roughness [4,1,3,5], or density [6] when rotated in a drum is seen to undergo radial segregation characterized by the formation of a core of smaller or rougher grains. This radially segregated core is seen to evolve into alternate bands of larger (or smoother) and smaller (or rougher) grains along the length of the drum [7,8]. Axial segregation is found to occur over a considerably larger time scale than radial segregation, which is usually complete within a few drum rotations. In a rotary kiln, radial segregation could lead to poor contact between the gas flowing above and the particles in the core, which would result in poor heat transfer and/or lower rate of reaction. Axial segregation, would lead to products of fluctuating qualities.

Analysis of granular segregation has been undertaken in some recent studies via discrete element simulations [9], and using coarse-grained continuum models [9,2,10]. A recent approach, which is the one followed in this work, is based on the theoretical formalism of Bouchaud, Cates, Ravi Prakash and Edwards [11]. Henceforth referred to as BCRE in this work, this study models grain transport on a sandpile surface, and has been employed in [12] for studying segregation during the filling of a silo with a mixture of two species. The “minimal” model of [12] describes the case of grains with equal sizes but with small differences in surface properties. The same formalism was used in [13] to demonstrate the possibility of complete segregation in a mixture of large smooth grains and small rough grains, and spontaneous stratification, i.e. alternating layers of the two species, for a mixture of large rough grains and small smooth grains. The minimal model of [12] was generalised by [14] to accommodate grains differing slightly in surface properties as well as size.

Two recent studies [15,16] have considered axial segregation in rotating drums, without using the BCRE approach as a basis. While [15] considers rapidly rotating drums of small radii in order to eliminate radial segregation, [16] studies the instability of a rather simplified radially segregated state to axial perturbations. Thus, both side-step the issue of determining the radially segregated state. Both models assume a flux of particles on the surface that is driven by the local slope, and [15] also defines a flux driven by the gradient in the local concentration. However, grain advection is not determined by the local slope, rather by the bulk velocity in the surface layer. Secondly, it is unlikely that a diffusive flux due to a concentration gradient could be important when the grain size is much smaller than the size of the drum.

In this work, we extend the formalism of [14] to address the problem of segregation in rotating drums of a granular mixture whose constituents differ in size and surface properties. The problem of segregation in rotating drums has been addressed in [17] for some special cases; however, our approach differs from theirs in some fundamental ways, which we will point out in this paper.

![Fig. 2. The coordinate frame for our model equations, showing some of the variables of interest](image-url)