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Correlations for shear-induced percolation segregation in granular shear flows

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ABSTRACT

Discrete element method (DEM) computer simulations are used to develop correlations for the mean percolation segregation speed and diffusion coefficient in a steady shear flow of a bi-disperse mixture of cohesionless, spherical particles. The simulations span a range of size ratios, dimensionless shear rates, and dimensionless applied normal stresses. The volume concentrations of the smaller species are small, with values between 0.04% and 9.6%. For the investigated set of parameters, the dimensionless mean percolation speed has an exponential dependence on the particle size ratio and is a linear function of the large particle concentration, but is independent of the dimensionless normal stress, at least for dimensionless normal stresses exceeding a critical value. Furthermore, the dimensional mean percolation speed is also independent of the dimensional shear rate. The diffusion coefficient, however, does depend on the shear rate, but asymptotes to the self-diffusion coefficient as the particle size ratio approaches one. The proposed correlations fit the simulation data very well, with coefficients of determination exceeding 0.99 and 0.98 for the percolation speed and diffusion coefficient, respectively. These correlations are intended for use with higher-level models, such as continuum models for granular flow, in order to predict segregation in large systems.

1. Introduction

Particle segregation is the unintentional de-mixing of one or more components in a mixture of particulates. Segregation is usually undesirable and generally appears during handling of free flowing particles when the components have varying properties, especially differences in size. Segregation can result in variable product properties and quality as well as inconsistent material handling behavior. Hence, significant effort is often invested in attempts to avoid or control segregation during processing and handling.

A large number of physical mechanisms leading to particle segregation have been identified. These mechanisms include, but are not limited to: inter-particle percolation, differences in fluid forces, differences in granular forces including drag and buoyancy, and differences in particle inertia [43,44,55]. Note that a variety of names have been given to these various mechanisms. Of particular interest for this article is inter-particle percolation.

Inter-particle percolation can be of two types: spontaneous and shear-induced. Spontaneous percolation results when one particle species is small enough to move under the action of gravity through the voids located between the larger, stationary species. Previous work [7,59] has shown that the critical size ratio below which spontaneous percolation occurs in a binary mixture of spherical particles is $d_f/d_c \approx 0.155$, where d_f and d_c are the diameters of the smaller (fine) and larger (coarse) species, respectively. There has been considerable prior research, both experimental and computational, focused on measuring the segregation speed of the smaller particles through the bed of larger particles as a function of the size ratio, system size, and particle interaction properties such as the coefficient of restitution and friction coefficient [7,33,37,58]. However, spontaneous percolation is not generally of great concern in industrial settings. Of more interest is shear-induced percolation (referred to as "percolation" for the remainder of this article for convenience), which is the focus of the current study.

Many previous experiments and discrete element method (DEM) studies have examined shear-induced percolation in geometries of industrial interest. These studies include ball mills [12,13,39], blenders [3,14,17,36,51], rotating drums [15,21,31,52,57], hoppers [2,29,48,56], and heaps and piles [35]. While these studies provide useful results for the specific geometries of interest, the quantitative findings are usually not applicable to other systems or even the same system at a different scale. Furthermore, DEM studies usually use particles that are much larger than those encountered in reality (or, alternately, the system dimensions are much smaller) due to computational constraints. Although these studies can provide good qualitative understanding, they may not provide good quantitative predictions.

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Studies of segregation in more fundamental geometries, such as in shear cells and down inclined surfaces have also been performed. The advantage of these geometries is that the flow properties of the system are usually well defined and controllable. Since shear cells are of particular interest in the current work, only those investigations are described here. Bridgwater and co-workers [8,45,49,50] and Puri and co-workers [28,53] used reciprocating shear cells to investigate the speed of percolating particles as a function of particle size ratio, shear rate, applied stresses, particle shape, and particle interaction properties. In these studies, a constant, uniform shear rate was assumed. The shear rate was held constant throughout most of the forward and backward movement of the cell, but transients necessarily occurred, although short in duration, due to the reciprocating nature of the device. In the Bridgwater studies, the upper and lower walls of the shear cell consisted of sieves, allowing the fines to steadily flow through the system rather than collecting in a particular region within the device. The Puri shear cell had a sieve just at the bottom; fines were not added into the system during operation. Percolation rates were correlated with particle size ratio, applied normal stress, strain rate, and material and surface properties. Bridgwater and colleagues observed that size ratio was the most important parameter in determining segregation speed. The normal stress was found to only be important when its value was large enough to deform the particles. The concentration of fines in these studies was limited to small values. Jha and Puri [28] studied segregation in initially mixed binary samples. The concentrations in these experiments were not limited to small values. They found that along with size ratio, strain rate was also an important parameter, especially as the size of the fines increased.

Fundamental studies have also been performed with annular shear cells. Annular shear cells have the advantage of being able to produce steady, uniform shear profiles without the transients and limited strain inherent to a reciprocating design. Stephens and Bridgwater [49,50] were one of the first groups to use an annular shear cell for percolation studies. They used tracer particles that were tracked by manually sampling material layer by layer within the cell. Comparisons of percolation rates were made with the reciprocated shear cell described previously, with the authors claiming a reasonable match. The simple geometry of the annular shear cell also makes it ideal for comparisons to theoretical and computational results. For example, Bridgwater et al. [8]; Golick and Daniels [24], and May et al. [34] used annular shear cells for model validation.

In addition to experimental and computational studies, several researchers have developed continuum-level models for shear-induced percolation segregation. The strengths of continuum models are that they can be applied at industrially relevant scales, they typically require less computing power for completing the predictions than discrete models such as DEM, and they provide fundamental insight into the relationship between variables. The downsides of continuum models, however, are that the models are often more challenging to develop, frequently require significant simplifying assumptions, and the parameters needed in the models are often unknown.

Bridgwater et al. [8] and Savage and Lun [41] developed some of the first continuum-based percolation models. Bridgwater et al.'s model was obtained by applying conservation of mass to the particle species, incorporating both advective and diffusive fluxes, although when comparing with annular shear cell experiments, the diffusive flux term was absent. The percolation speed, used in calculating the advective flux, was an empirically derived function of the size ratio, which was obtained from shear cell experiments [8]. Although they acknowledge the importance of strain rate and fines concentration, they did not include the percolation speed's dependence on these parameters in their model comparisons to experiments. Although their model predictions compared well against transient experimental data during early time periods, significant discrepancies occurred for later periods, likely due to their simplifying assumptions.

Savage and Lun [41] model assumed that percolation was caused by two effects: smaller particles falling through the random gaps between larger particles, referred to as a "fluctuating random sieve", and a size independent "squeeze expulsion" mechanism, which accounts for particles getting squeezed by neighboring particles out of a given layer. The latter mechanism was introduced to satisfy overall mass conservation. They provided a framework based on statistical mechanics and conservation of mass to predict the rate of each of these processes. Savage and Lun used their model to predict segregation in a fully developed inclined chute flow, with the model showing reasonable agreement with experiments in some instances, but large differences in others. In addition, several fitting parameters related to the packing of particles were also required for model closure.

Gray and Chugunov [60], Thornton et al. [54], and Fan et al. [22] developed modeling approaches for bi-disperse mixtures that require only two dimensionless input parameters. The models were applied to study segregation during the formation of granular avalanches and heaps. These more recent continuum models have shown better predictive success than Bridgwater et al.'s and Savage and Lun's earlier work. Gray and Thornton [25] also developed a continuum model, but only had a single parameter accounting for advection. In the continuum equations, the interaction drag between the two phases was assumed to be of the Darcy type. A simple model for overburden pressure for each phase was the second major assumption. The percolation velocity of a phase was found to have a first order dependence on the concentration of the other phase, similar in form to Savage and Lun [41] model. In the subsequent work by Gray and Chugunov [60], a diffusive flux accounting for mixing effects was included. A DEM-fitted value for the ratio of the advective to diffusive fluxes, expressed in terms of a segregation Péclet number, was generated by Thornton et al. [54] using an inclined chute flow. They obtained good agreement between their multiscale model and DEM-only simulations of segregating flow down an inclined plane. The authors noted, however, that a more generalized method for determining the Péclet number is required for broader application.

Besides comparison with DEM simulations, Gray and Thornton's model has also been compared with experiments. May et al. [34] compared results from their annular shear cell experiments to Gray and Thornton's continuum model. In May et al.'s work, the height of the cell was measured in an initially normally-graded, bidisperse mixture of spheres. The objective of their experiments was to correlate the segregation phenomenon with the changes in height or the packing density of particles. The original continuum model, however, did not capture the change in bed height during segregation; hence, a constitutive relation between packing density and concentration was implemented. The predicted height using this revised model was able to predict the experimental bed height at initial times, but was not accurate at later times.

The recent work by Fan et al. [22] involved a Péclet number and a second dimensionless number, which is a ratio of advective and segregation time scales. Note that in this work, the advective component corresponds to the bulk flow rather than the mean flow of fines. Similar to Thornton et al. [54], in order to provide closure relations to their continuum models, Fan et al. [22] made use of DEM simulations. Their DEM simulations were performed for the same geometry as their experiments: material flowing down a quasi two-dimensional heap. They back-fit their segregation model's two dimensionless parameters to the DEM data for a range of conditions. Using this information, they were then able to quantitatively predict experimental results using their continuum-DEM model.

The recent modeling techniques involving DEM have improved the predictive capability of the continuum models, although there are similarities between the old and new approaches. For example, the model used by Thornton et al. [54] has elements and definitions similar to Bridgwater et al. [8] advective-diffusive model. Similarly, the first order concentration dependence of the segregation rate term is a common element in the models by Fan et al. [22] and Savage and Lun [41].