Sensitivity of granular segregation of mixtures in quasi-two-dimensional fluidized layers

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Size segregation is studied using a quasi-two-dimensional rotating cylinder system for mixtures of different size, near-spherical particles. Flow occurs only in a thin surface layer, whereas the remaining particles rotate as a fixed bed. In most of the systems studied, the measured radial weight fraction profiles in the bed show significant *double segregation* (a core of small particles as well as a thin layer of small particles at the periphery). The profiles are found to be sensitively dependent on the surface roughness of the particles in the mixture, and double segregation reduces with particle roughness. Double segregation is also sensitive to cylinder diameter and no double segregation is observed for the smaller diameter cylinders used. The system, however, shows two unexpected scalings: (i) the scaled profiles are nearly the same for different cylinder diameters, when the cylinder diameter to the cylinder length ratio is the same, and (ii) the profiles obtained are found to be insensitive to the size of the large particles in the mixture but depend strongly on the size of the small particles.

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Flowing granular mixtures segregate, and this can have a significant impact in many industrial processes ranging from pharmaceutical tablet manufacture to cement production. The process, however, is not understood to the level that quantitative predictions can be made. Even predicting the direction of segregation is not trivial. For example, Hong *et al.* [1] showed using molecular dynamics simulations that fluidized binary mixtures of elastic spheres under gravity segregate with the larger particles on the top or the bottom of the layer, depending on the temperature and the diameter and mass ratios. They obtained a criterion to predict the direction of segregation based on competition between condensation and percolation. Jenkins and Yoon [2] showed that kinetic theory also yields a similar criterion for the direction of segregation. Reversals in the direction of segregation have been observed in flowing fluidized layers as well, but the situation in this case is complicated by dissipation and gradients across the layer [3,4].

Segregation in fluidized layers has been studied in a number of systems including heap flows [5–7], chute flows [3,8–10], and rotating cylinder flows [9,11–19]. In most experimental systems involving size segregation, the larger particles are at the top of the flowing layer and small particles are at the bottom. There are a few exceptions. Nityanand *et al.* [11] reported reverse segregation in a rotating cylinder system (small particle concentrate at the top of the flowing layer at high rotational speeds). Dolgunin and Ukolov [8] found small particles concentrated at the top and bottom of the layer with larger particles concentrated near the middle of the layer in a chute flow. We refer to this as double segregation since it involves regions of regular and reverse segregation. Thomas [9] also found double segregation in rotating cylinders considering a few large particles in a mass of small particles. She showed that the average radial position of the larger particles could be varied over the entire possible range by changing the size of the small particles.

We study here size difference driven segregation in quasi-two-dimensional (quasi-2D) rotating cylinders. The flow comprises a thin surface flowing layer, while the remaining particles rotate as a fixed bed. Segregation occurs in the fluidized flowing layer and determines the distribution of particles in the fixed bed. The radial weight fraction profiles of the small particles in the fixed bed are measured. We find that the radial profile, and thus the distribution in the flowing layer, is sensitively dependent on the system parameters. We also find simple scaling with respect to some parameters of the system.

Radial segregation experiments were carried out in quasi-2D cylinders with different diameters (16 cm, 24 cm, 32 cm) and lengths (1 cm, 1.34 cm, 1.5 cm, 2 cm). The cylinders were rotated by a computer controlled stepper motor. Mixtures of monodisperse spherical balls of different diameters (1, 1.5, 2, and 3 mm) and different materials [stainless steel (SS), brass, and mild steel (MS)] were used. In all the experiments the cylinder was filled 50% by volume with mixtures of specified compositions and rotated at a specified speed (3, 6, 12 rpm) for 150 revolutions to achieve a steady state. The flow was in rolling regime [20]. To measure the bed profile, the cylinder was removed from the drive, placed on an inclined surface and the top face plate was replaced by a sampling plate with twenty-three 11 mm holes at 13 different radial positions. The holes were sufficiently far apart and the sequence of sampling was such that sampling from one hole did not disturb the particles under the neighboring sampling holes. To ensure that sampling was done only in the fixed bed region, no sampling points were included in a strip near the free surface and in the triangular wedge formed by the final avalanche when the cylinder was suddenly stopped. A closely fitting, knife-edged steel tube (inner diameter 10 mm) was inserted in turn in each sampling hole until it touched the bottom plate and only particles inside the tube were collected by means of a vacuum probe. This ensured that the volume of material sampled was precisely controlled and relatively small (~ 0.8 cm^3). A small sampling volume is essential to obtain a good spatial resolution. The sample

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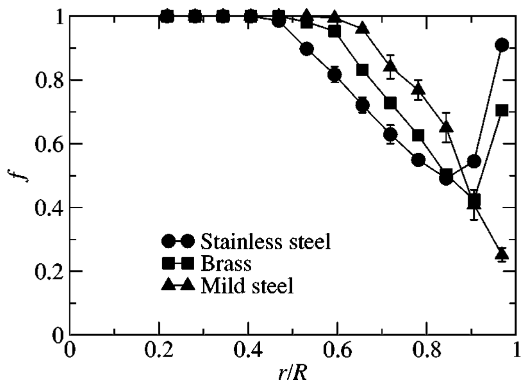

FIG. 1. Variation of the weight fraction of small particles (f) with scaled radial distance (r/R) in a 75% mixture of 1 and 2 mm stainless steel, brass, and mild steel particles.

was sieved to obtain the weight fraction of the small particls (f). Each experiment was repeated at least three times. Although the sampling volume was small, we found a maximum error of 6 wt % even for the largest particles (3 mm) used. As a result of multiple sampling points at a given radius for each experiment and repetition of experiments, each data point reported is an average of at least six measurements and the standard deviation is shown in each case. The experimental procedure allows us to measure the equilibrium radial profile with reasonably high accuracy and spatial resolution.

The effect of material properties was found to be very significant and results for three different materials are shown in Fig. 1 for mixtures of 1 mm and 2 mm particles. Stainless steel has the greatest extent of reverse segregation (region $r/R > 0.8$ in Fig. 1 followed by brass and mild steel which has no reverse segregation). In the case of mild steel which particles, the 2 mm particles were smooth but the 1 mm particles were rough since they were slightly rusted. The surface roughness of the small particles appears to be the primary distinguishing feature between the three systems. The static and dynamic angles of repose, which are a measure of the interparticle friction, are the highest for the 1 mm mild steel balls and lowest for the 1 mm stainless steel balls (Table I). The angles for the 2 mm particles were nearly the same for the different materials. The static angle of repose is taken to be the angle of the free surface when the cylinder under steady flow is suddenly stopped. The dynamic angle of repose is the angle of the free surface at the mid point when the particles are in steady motion. SEM photographs (Fig. 2) indeed show that the surface is roughest for MS balls and smooth for the SS balls. The strong dependence of the segregation on the surface roughness is surprising and has not been previously reported.

TABLE I. Static (β_s) and dynamic (β) angles of repose at angular speed 3 rpm for 1 mm particles.

Material	β_s (deg)	β (deg)
SS	15.8 ± 0.1	26.5 ± 0.2
Brass	20.2 ± 0.1	33.4 ± 0.2
MS	22.4 ± 0.2	34.2 ± 0.2

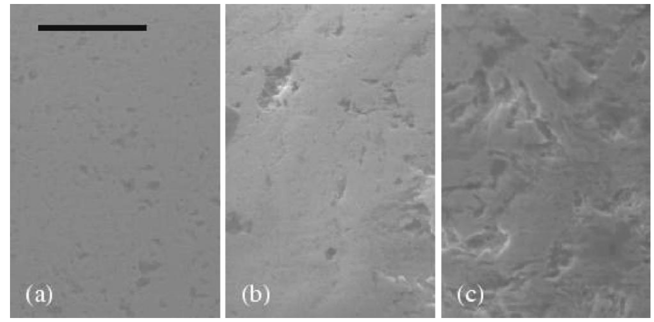

FIG. 2. Scanning electron micrograph of the surface of 1 mm (a) stainless steel, (b) brass, and (c) mild steel balls. The bar in the images is 50 μm long.

All the remaining results in our paper are for smooth stainless steel particles, and the effect of different system parameters is reported. Some of the trends observed but not shown in detail are as follows. Increase in speed of rotation was found to significantly decrease the extent of reverse segregation, but reverse segregation was nearly unchanged with a fraction of the cylinder filled. Increasing surface roughness of the cylinder end plates also reduced the extent of reverse segregation. We present below results showing the effect of system size, particle size, and mixture composition.

Cylinder diameter and length were found to have a significant effect on reverse segregation. For a given mixture, reverse segregation decreased with reducing size of the cylinder [Fig. 3(a)], and no double segregation was observed for the smallest cylinder used (16 cm diameter). Perhaps this explains why double segregation has not been commonly observed previously: most previous studies used relatively small diameter cylinders [9,12,14,21]. Increasing cylinder length from 1 cm to 2 cm for a fixed diameter of 32 cm reduces the extent of reverse segregation [Fig. 3(b)]. With further increase of cylinder length to 3 cm the profile becomes considerably flatter [Fig. 3(b)]. We found that this is because of axial segregation. It is remarkable that axial segregation occurs in cylinders with such large diameter to length ratios ($D/L \sim 10$). Axial segregation was not obtained in any of the other systems studied.

In spite of the complexity of behavior with changing cylinder length and diameter, the scaled radial profiles are nearly invariant when D/L is kept constant. Figure 3(c) shows profiles for three different diameters, but the same D/L ratio ($D/L = 16$). The inset in the figure shows similar scaling of profiles for systems with $D/L = 24$. The results indicate that reverse segregation increases with increasing (D/L) values. The strong dependence on D/L indicates that system size effects are significant. At the same time, the scaling results imply that the segregation is independent of d/L (ratio of particle diameter to cylinder length).

Consider finally the effect of mixture composition and particle size on the radial weight fraction profile of the small particles [$f(r)$] which is shown in Fig. 4. Double segregation is seen even for the smallest size ratio studied (1 mm:1.5 mm, Fig. 4), indicating that reverse segregation occurs in this system even when the large particles are not too massive. Double segregation is obtained for all compositions although the extent of reverse segregation at $r/R \sim 1$ decreases with

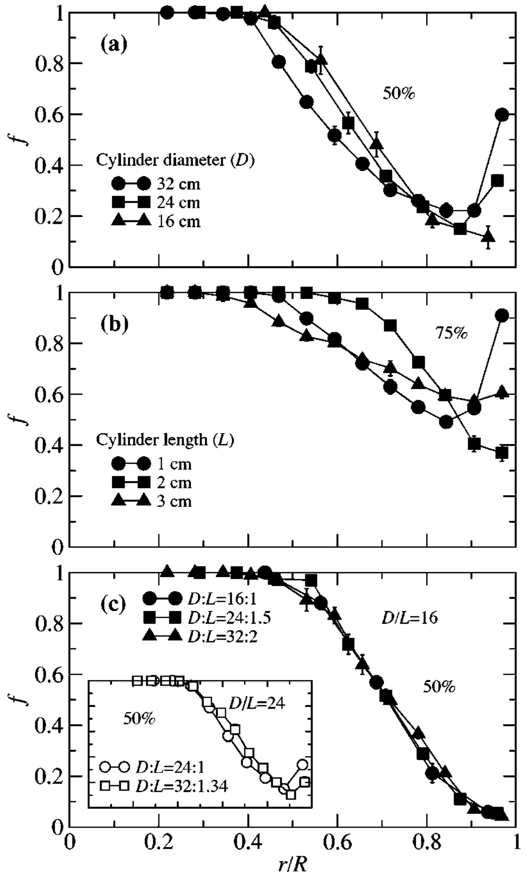

FIG. 3. Variation of the weight fraction of small particles (f) with scaled radial distance (r/R) in a mixture of 1 and 2 mm SS particles. (a) Cylinders of different diameters and length 1 cm are used with 50% small particles. (b) Cylinders of different lengths and diameter 32 cm are used with 75% small particles. (c) Cylinders of various diameters and lengths but the same D/L are used with 50% small particles.

increasing amounts of the large particles. The results also indicate that the radial concentration profile is nearly independent of the size of the large particles for a fixed mixture composition and fixed size of the small particles. The profiles for 1 mm and 2 mm mixtures are nearly the same as those for 1 mm and 3 mm mixtures (Fig. 4). Further, the profiles for mixtures of 1 and 1.5 mm particles are nearly the same as those for the mixtures of 1 and 2 mm particles as well as 1 and 3 mm particles (Fig. 4).

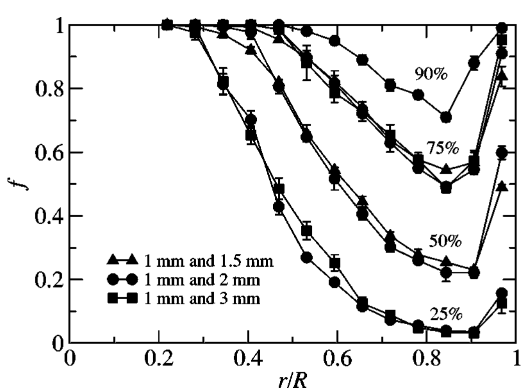

FIG. 4. Variation of the weight fraction of small particles (f) with scaled radial distance (r/R) in mixtures of 1 mm and 1.5, 2, and 3 mm particles for different mixture compositions indicated.

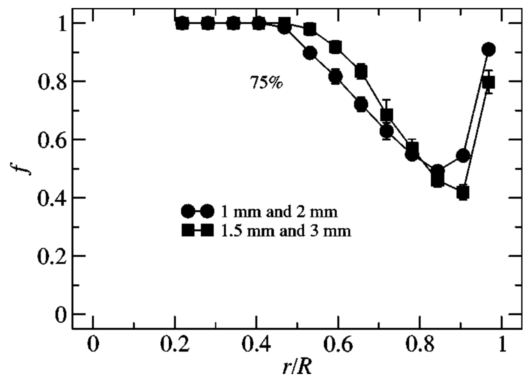

FIG. 5. Variation of the weight fraction of small particles (f) with scaled radial distance (r/R) for mixtures with different size steel balls as indicated. Mixtures comprise 75% small particles.

In most previous studies it has been assumed that the extent of segregation depends essentially on size ratio [8,12]. However, we find that the profiles are quite different when the size ratio is the same and the size of the small particles is varied. For example, the profile for a mixture of 1.5 and 3 mm particles is different from that for a mixture of 1 and 2 mm particles as shown in Fig. 5. The size ratio in both these cases is 2. The above results show that segregation is nearly independent of the size ratio for fixed size of the small particles but profiles for the same size ratio and different sizes are different. These results do not contradict the earlier works of Dury and Ristow [13] and Thomas [9] since in both these studies the size ratio is varied by changing the size of the small particles keeping the large particles the same.

The data presented here for size segregation in quasi-2D rotating cylinders indicates complex behavior. We discuss the results and their implications in qualitative terms below. At steady state, there is a one-to-one correspondence between the bed profile and the profile in the flowing layer at its midpoint. The length scale in the bed is magnified by a factor of 20 relative to that in the layer, making measurements easier. The profiles measured in the bed thus reflect in some detail the processes in the flowing layer where the segregation occurs. The double segregation observed in some cases indicates that the direction of segregation changes with depth in the layer. The most likely cause for this is the varying solids volume fraction and granular temperature across the layer. Theory and simulations indicate that smaller particles rise relative to the larger ones in high temperature and low density regions typical of the upper part of the flowing layer, whereas the reverse is true in the densely packed regions in the lower parts of the layer [3].

The sensitive dependence on surface roughness of the particles is unexpected. Experimental results indicate that particle surface roughness and shape have only a small effect on flow, for example, very similar flows are obtained for sand and glass particles of the same size [22]. The effect of surface roughness on segregation could be due to increased dissipation leading to a slightly higher density of the upper region of the bed which would suppress the reverse segregation. The invariance of the profiles with the size of the large particles is also an unexpected result. The finding is consistent with a picture that small size differences are sufficient to cause segregation and once the size difference exceeds a certain value the driving force for segregation saturates. Finally, we note that the results presented are for a quasi-2D system and system size effects are important. However, wall effects do not appear to be significant since results are independent of the particle size to cylinder length ratio.

The experimental results reveal several different phenomena which can be rationalized qualitatively using known mechanisms of size segregation. A quantitative description would, however, require detailed information about the flow and kinematics in the layer, which at present is lacking.

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