Convection and size segregation in a Couette flow of granular material

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We have investigated the size segregation of a binary mixture of spherical glass particles in a Couette geometry, where the cylinders are made of smooth glass and the flow is generated by the shearing motion of the inner cylinder. The trajectories of 1, 2, and 3 mm glass particles, placed at the bottom of the cell, were followed as they moved through a 1 mm medium. We observe convective motion of the particles in which particles rise at the outer radius and fall at the inner radius. The horizontal and vertical speeds of 2 and 3 mm glass particles, initially at the cell bottom, as a function of the inner cylinder speed were determined and the onset of turbulent motion measured by processing images. While in all cases the larger particles rose to the top and remained on the surface as rotation continued, the particles comprising the medium appear to go through a convectivelike motion. The effect of interstitial fluid, in this case air, was studied by repeating the experiments in vacuum. We did not detect any significant changes in the results. [S1063-651X(97)14010-7]

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I. INTRODUCTION

In this paper we present an experimental study of the flow of 1 mm spherical glass particles under shear in a Couette geometry where the inner cylinder is rotated while the outer cylinder is stationary. This geometry allows for vertical, radial, and azimuthal movement of the glass particles. As the control parameter, the rotational rate of the inner cylinder, is adjusted to different values, a variety of dynamical behaviors can be seen including dilation, convective motion, and, when more than one particle size is present, segregation.

There are many aspects of the physics of granular material that are distinctly different from solids and liquids [1–4]. The most distinctive feature is the phenomenon of arching. Granular material is inherently inhomogeneous, and the force network providing the stability of the system is nonuniform. This force network is set up by the grains in contact with each other and the container's walls. The distribution of forces in a random network is related to the rigidity threshold of the entire granular array. In general, this is a nonlinear problem [5]. In a random configuration of grains there will be places where arches appear naturally, leaving empty regions below. The packing structure of the granular material is crucial in the stability of the force network. The force network and the shape of the free surface depend on factors such as the packing, degree of nonuniformity of the grains, and existence and the shape of the side walls.

The densest possible packing in three dimensions is the close-packed hexagonal structure with a packing density of $\eta \approx 0.74$ [6]. The lowest possible random packing, for immersed glass spheres in a liquid with variable specific density, where the glass particles float is $\eta \approx 0.56$. In this limit the system is barely stable [7]. A comparison of the most dense to a barely stable configuration corresponds to a ratio of 1.1 in the intergrain distance.

The phenomenon of arching in the granular material causes the pressure throughout the material to be nearly a constant. The constancy of pressure is maintained by the tenuous force network generated by the grains in contact with each other and the walls. In a liquid pressure changes with the height of the column of the liquid. The rate of flow from the bottom or side of a container filled with fluid depends on the pressure, that is, the height of the column above the opening. As a result, the flow rate will diminish as the container empties itself. In an hourglass the sand flows continually like a liquid, but the discharge rate is nearly a constant, which indicates independence of pressure on the height of the column [8].

Dilatancy is another significant feature of the granular material relevant to our experiment. A granular material must expand in order to flow or deform. Dilatancy arises from the need of a densely packed material to spread in order to make room for passing grains.

A source of dissipation or friction in these materials arises from the relative motion of one particle with respect to another. Therefore, it should depend on the shear rate [9] $\dot{\gamma}$. There are two sources of energy loss. The kinetic energy lost in collision will be proportional to the square of the shear rate. In the presence of gravity the fall of the particles through the holes will also contribute to the energy loss and constitutes a second source of friction, one that depends inversely on the square of the shear rate [9]. The interstitial fluid can also contribute to the loss and is characterized by the Bagnold number [10], defined by the equation below, which represents the ratio of the intergrain collision forces to the viscous forces.

$$B=(\rho_s D^2 \lambda^{1/2} \dot{\gamma})/\mu,$$

where ρ_s is the density of the granular material, D is the grain diameter, λ is the linear concentration, $\dot{\gamma}$ is the mean shear rate, and μ is the interstitial fluid viscosity. For B

>400 the interstitial fluid effect may be ignored. Our experiment is done in air where $B \approx 100\,000$ so the effect of air friction can be neglected.

In contrast to ordinary fluids and gases, in a gravitational field, where particles are distributed according to their density, in a mixture of shaken granular material larger particles are found to rise and segregate at the top of a mixture. This problem recently was modeled by large-scale computer simulations [11,12]. The simulations supported the earlier explanation of segregation where it was proposed that the upward motion of particles in the shaking experiments had to do with smaller particles filling the voids generated underneath the larger ones during each shaking event. Thus, it was supposed that local avalanching underneath the larger beads resulted in the upward motion.

More recent experiments suggest that size segregation can arise from a fundamentally different mechanism, namely, convection [13]. These experiments show the strong dependence of convection on the nature of the boundary conditions at the walls, that is, the shape of the walls and the frictional interaction between them and the grains. Boundaries play a crucial role in initiating and sustaining any relative particle movement in granular materials. In this regard these materials behave very differently from ordinary fluids, where buoyancy forces can drive the convection. Convection appears to be directly linked to the interaction of grains with the container's walls. In the experiments on granular materials where a convective mechanism was at work it was also shown that for smooth, slippery walls convection was greatly reduced. The recent two-dimensional simulations by Taguchi [14] and Gallas *et al.* [15] clearly indicate that strong inelastic interaction between grains and the walls is necessary to produce convection cycles. This is also consistent with the experimental results of Clement *et al.* [16]. Although it is clear that boundary conditions at the walls are important for creating convection, the precise nature of the interplay between frictional force and the shape of the walls is only partially understood.

Size segregation under shear occurs in many natural and industrial processes. When a mass of particles comprised of different sizes is deformed in the presence of a gravitational field, segregation or grading of the particles can occur. For centuries mineral processing equipment has achieved particle segregation this way. In other instances, such as pharmaceutical processes, size segregation is an undesirable occurrence [17]. The mechanism responsible for segregation in these circumstances is still not well understood.

Shearing motion can be generated by relative displacement of one or two opposing surfaces with respect to the granular material. Flow down an inclined chute or a natural hill, and flows, like the one in our experiment, generated by shearing action of one of the walls of the container with respect to the material are examples. The shearing flows are divided into low and high velocity limits based on the dominant physical mechanism involved. In the low velocity limit [14], the medium has a relatively high bulk density where particles are nearly in continuous contact with one another and overriding each other during the shear process. In the high velocity limit [2], the particle density is low and particles interact vigorously and primarily through instantaneous collisions. The diffusive processes that are ignored in the low velocity limit become dominant in the rapid flows. In this paper we primarily focus on the low velocity flow. Savage and Lun [18] have given an analysis of the flow of a binary mixture of small and large spherical particles of equal mass density down an inclined chute in this limit. They analyzed the flow in terms of layers in relative motion with respect to one another as a result of the mean shear developed by the rough lower boundary. As a result of overriding adjacent layers the network of void spaces goes through a continual random change; in addition, the probability of finding a hole that a small particle can fall into is larger than the probability of finding a hole that a larger particle can fall into. Hence there is a tendency for particles to segregate out, with fine ones at the bottom and coarse ones at the top. While this mechanism seems plausible, experiments of Foo and Bridgwater [19] suggest that some other mechanism can also be at work. They investigated the migration of a single large particle in a sheared mass of smaller ones. It was found that the single larger particle migrated towards the region of higher shear in which there was a greater mobility of smaller particles.

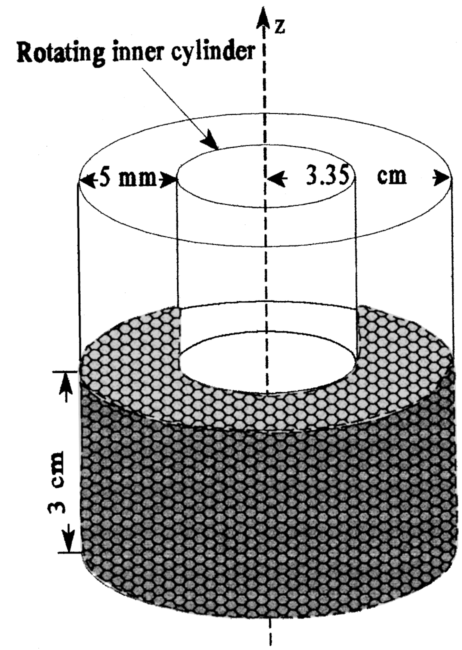

FIG. 1. The Couette apparatus.

II. EXPERIMENTAL SETUP

Figure 1 shows the apparatus used in our experiments. It is basically a Couette flow apparatus consisting of two coaxial vertical cylinders, in this case made up of glass or plexiglass, open on the top, where the outer cylinder is fixed and the inner cylinder is free to rotate with the help of a dc motor. The apparatus is mounted on a carefully leveled heavy platform. The outer cylinder has an inner radius of 3.35 cm and the inner cylinder has an outer radius of 2.85 cm. The length of the cylinders is 8 cm. The space between the two cylinders, $D=5$ mm, was then filled to a height h with spherical glass beads of diameter $d=1\pm0.05$ mm. For experiments described in this paper $h=3$ cm. The beads are not strictly monodisperse. A larger spherical glass bead of the same composition and density as the smaller ones was placed at the bottom of the column. In order to follow the motion of the large bead through the medium we painted it with ink (thus leaving its size, density, and elastic properties unchanged). The bead packing was sufficiently transparent to allow direct optical measurement of the location of the painted bead due to the small ratio of D/d. The inner cylinder was then rotated at a fixed angular frequency while a video recording was made of the apparatus as seen from the side. The time and position data were extracted from the recording. The time data precision is limited to the duration of a frame, i.e., 1/30 of a second. This introduces an error that is not significant in most of our experimental runs since the maximum angular frequency of rotation is 3 Hz and the average angular frequency of the beads is about one-fourth of the angular frequency of the inner cylinder. The vertical and horizontal position measurements were made with an accuracy of 0.2 mm or better.

III. RESULTS

A. Observation of the motion and measurements of the vertical and the horizontal speeds, V_z and V_0 of a 2 mm marker in a 1 mm medium

1. Initial sets of experiments

These were aimed at a semiquantitative characterization of the motion of a larger particle, in this case either 2 or 3 mm in diameter, placed at the bottom of the pile of 1 mm particles subjected to shear by rotating the inner cylinder at a specific angular frequency. The spacing between the outer and inner cylinder is 5 mm so there are approximately five layers of material between the two cylinders. We will refer to them by numbers from 1 to 5 counting up from the outer cylinder. In order to search for a reliable pattern of motion each experiment was repeated many times.

The following general observations were made for the medium and the marker. All layers in the medium, including the first layer (the layer in contact with the outer cylinder), are in motion and rotate about the axis of the cylinder. The closer a layer is to the inner cylinder the larger is its angular velocity. However, the fifth layer (the layer in contact with the inner cylinder) is moving at a much lower angular velocity than the inner cylinder, indicating slipping motion due to the smooth boundaries. In addition to the rotational motion, all particles move up and down (along the axis of rotation) and in and out in the radial direction.

The motion of the 2 mm marker is simpler and has a definite direction. The general pattern for the motion is that the marker rises to the top while it is in the two outer layers. When it reaches the top surface it moves inward and stays very close to the inner cylinder wall and, depending on its size, will ride over the two or three layers adjacent to the inner wall on the top surface. In addition, the marker is never seen to be rising while in contact with the inner wall. This pattern of motion is independent of the initial condition of the marker. For example, when we placed the marker initially at the bottom against the inner wall, it moved toward the outer wall and rose to the top while staying near that wall. The upward motion of the marker does not always follow the same pattern. In some runs it steadily rises to the top and in some others it moves up quickly to a height of 1–1.5 cm where it gets bumped into the inner layers for a while. At this time its vertical position fluctuates very little until it gets bumped back into the previous position near the outer wall where it resumes its upward motion to the top surface. The fraction of runs where this hesitation occurs decreases with increasing inner cylinder rotation speed.

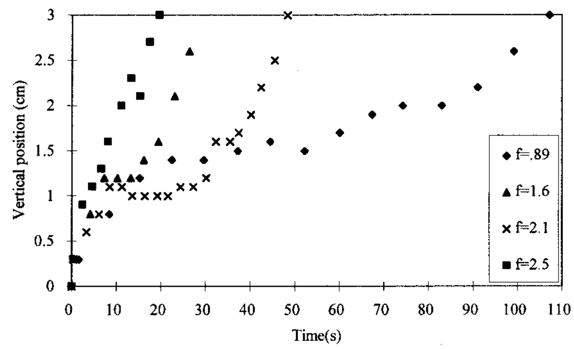

FIG. 2. Vertical position z of a 2 mm marker in a 1 mm medium vs time for various drive frequencies in a glass cell.

Figure 2 shows typical experimental runs for the vertical position of the marker bead versus time, in a 1 mm medium, for various inner cylinder rotational frequencies. For a particular inner cylinder rotation frequency the slope of the graph at the low and at the high ends are very close in value for the range of frequencies investigated (0.89–2.5 Hz). However, there is a slight detectable increase in V_z within the last 4–5 layers from the top surface.

2. The average vertical speed of the 2 mm markers

The average vertical speed, measured as a function of inner cylinder speed, was obtained by using the height of the column, 3 cm, and the total time taken by the marker to reach the top surface for 20 runs. Figure 3 shows a plot of the average vertical speed of the marker versus speed, V_{in}, of the inner cylinder. It is evident that V_z increases with V_{in}. However, the data seem to fall into three different regimes. In the low velocity regime ($V_{in} \leqslant 15$ cm/s or $f \leqslant 1$ Hz), V_z increases linearly with the drive speed. In the mid-range (15 cm/s$\leqslant V_{in} \leqslant 25$ cm/s or 1 Hz$\leqslant f \leqslant 1.5$ Hz) V_z is roughly constant. For $V_{in} \geqslant 30$ cm/s or $f \geqslant 1.5$ Hz there are large variations in V_z, although, generally, the speed of the marker

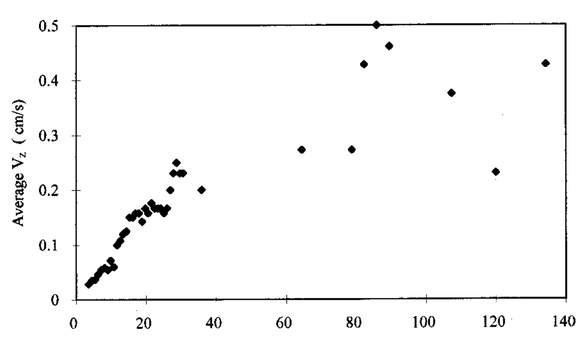

FIG. 3. Average vertical speed V_z of a 2 mm marker in a 1 mm medium vs speed of the inner cylinder in a glass cell.

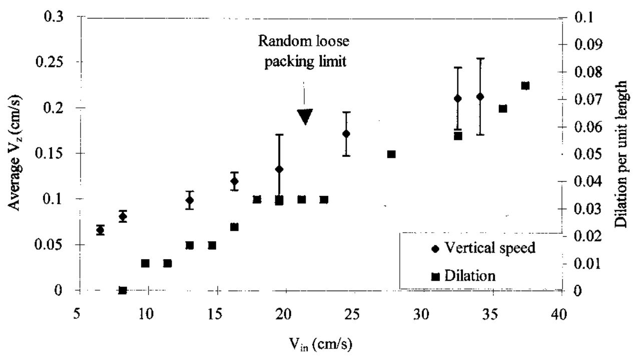

FIG. 4. Average vertical speed V_z of a 2 mm marker in a 1 mm medium and dilation per unit length of the medium vs the inner cylinder speed in a glass cell.

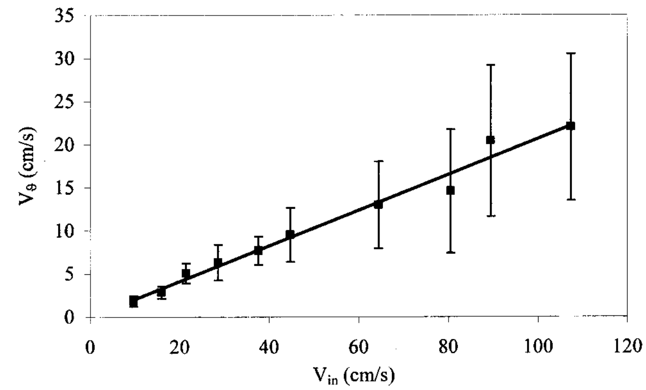

FIG. 5. Average horizontal speed V_0 of the 2 mm marker in a 1 mm glass medium vs the inner cylinder speed (glass cell). The slope is $\frac{1}{5}$.

is greater than for the two lower V_{in} regimes. In Fig. 4 the size of the bars is based on the standard deviation of V_z, and is calculated by repeated measurement of the average vertical speed at a given inner cylinder rotation speed. Although we refer to these as error bars, they actually give a measure of the intrinsic fluctuations associated with the flow. The sudden change in the size of the error bars for $V_{in} \geqslant 20$ cm/s is significant and we will return to it below. Table I shows the average vertical speed for the 2 and 3 mm markers in a 1 mm medium at an inner cylinder speed, $V_{in} = 8.95$ cm/s, that falls within the lower regime. The larger marker has a slightly higher vertical speed. This effect was also observed at higher inner cylinder speeds, V_{in}. In addition it was found that the average values of vertical speeds did not depend on the initial positioning of the marker at the bottom with respect to the inner wall.

3. The average horizontal speed of the marker V_θ

From the measurement of the time taken for the marker to make a complete revolution the average horizontal speed V_θ was determined. Figure 5 shows the average of this speed over the number of cycles taken to reach the top surface. The error bars are based on the range of values of V_θ found for each of the cycles of the motion of the marker before it reaches the top surface. Figure 5 shows a general increase in the speed of the particle with the increase of the inner cylinder speed and, approximately, the average marker's speed V_θ is about 1/5 of the inner cylinder speed. The size of the error bars increases rather significantly as V_{in} increases, indicating that V_θ becomes more nonuniform as the marker rises to the top. In the interval of $V_{in} \leqslant 20$ cm/s (or $f \leqslant 1.2$ Hz) V_θ is uniform and remains more or less a constant as the marker rises to the top surface. This interval coincides with the lower regime mentioned above for V_z. This result could indicate the constancy of pressure throughout the system in this interval. Figure 4 shows the amount of dilation per unit length as a function of rotation speed. The packing density at rest for our medium, η, is about 0.59 ± 0.01. At about $V_{in} = 20$ cm/s the packing density reaches the limit of the random loose packing (RLP) $\eta = 0.56$ where the constancy of pressure and the arching mechanism breaks down. Very possibly the large error bars in measurements of V_θ and V_z are due to the breakdown of the arching system and occurrence of local avalanches.

The packing density was determined by pouring the glass beads into a container using a funnel and leveling the surface by brushing the material on the surface gently to attain a level surface along with some tilting of the container from side to side (which could be thought of as very slow horizontal shaking).

Table I shows the average horizontal speed of 2 and 3 mm markers in a 1 mm medium at the inner cylinder speed of 8.95 cm/s (well within the first regime). The horizontal speed of the 2 mm marker is larger than 3 mm while inside and

TABLE I. A summary of the average vertical speed V_z and average horizontal speed V_θ for 2 and 3 mm markers in a 1 mm medium where the rotation speed of the inner cylinder $V_{in} = 8.95$ cm/s. No data are provided when the particle was not observed in the layer.

		Average horizontal speed V_θ (cm/s)			
Marker diameter (mm)	Average vertical speed V_z (cm/s)	Vertical interval (cm)	First layer	Second layer	Top surface (4th or 5th layers)
3	0.11 ± 0.05	0–3	2.1		3.3
		0–1		2.4	
2	0.08 ± 0.03	1–2	1.9	2.8	
		2–3		2.8	3.6

smaller when they are on the top surface. This difference could be explained in terms of the layers that each particle is in contact with while inside as well as on the top surface.

B. Segregation and the role of the interstitial fluid

One of the most significant outcomes of our experiments, as reported above (Sec. III A), is that glass particles larger than the size of the particles that make up the medium, in this case 1 mm, would segregate out to the top surface and remain there as the rotation of the inner cylinder continues. Initially, we suspected that the interstitial fluid, in this case air, had an effect on the segregation dynamics. To check the role of air in this process we repeated the experiments described in Sec. III A under vacuum (20 μm). The segregation process took place and there were no significant changes in the speeds. However, in the absence of air, less torque (about 5%) was needed for maintaining the same inner cylinder speed.

C. Examination of the motion of the 1 mm marker in a 1 mm medium

The dynamics of the 2 mm marker summarized above raises an intriguing question as to whether there is a convective mechanism affecting all the particles irrespective of their sizes or if there is another mechanism that is size dependent. We decided to experimentally investigate this question by following the motion of a 1 mm particle, in the medium, as the inner cylinder rotates. We recorded the position of a 1 mm marker, using the video camera, when it was moving within the first three outer layers. The marker was easily observable by eye when in contact with the inner cylinder (the fifth layer). In this way the presence of the marker in the fourth layer could be deduced by a process of elimination.

We ran the experiment repeatedly at a fixed rotation frequency of 0.50 Hz, which corresponds to $V_{\mathrm{in}}=8.95$ cm/s, and is well within the first region of Fig. 3. At this rotation speed the packing density of our medium is above RLP, allowing for stable arches to be formed. In addition the experiments were repeated with various initial conditions for the position of the 1 mm marker. Videotaping the motion of the marker for about 2 h resulted in a number of observations.

(a) The general motion of the marker, initially placed on the top surface, is as follows: The marker heads down while in contact with the inner wall or the layer adjacent to it, then it begins to make its way up. The upward motion, unlike the motion of the 2 mm marker, is not steady; and there are many short falls and rises on its way up; see Fig. 6. This demonstrates an overall convective flow.

(b) While observing the experiment we found that the marker never rises up when it is in contact with the inner wall. Even though the marker does fall occasionally while it is in other layers, the longest and fastest falls occur when it is in contact with the inner wall or the layer just adjacent to it.

(c) The marker's motion parallel to the axis of the cylinder does not follow an orderly pattern. Figure 6 shows the vertical motion of the particle and the points are marked by indices that indicate the layer the marker was found in at the time of observation. The camera records the position of the marker once every cycle of the marker's motion. Whenever

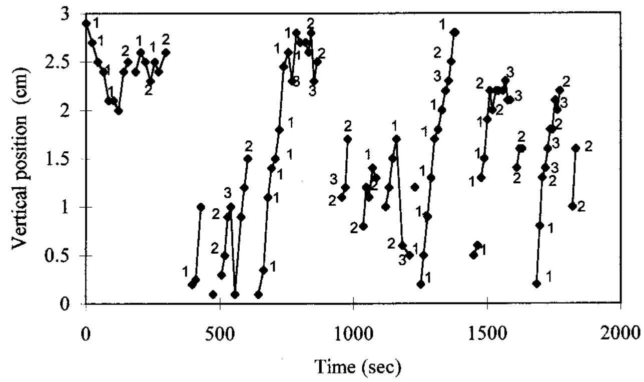

FIG. 6. Vertical position z of a 1 mm marker in a 1 mm medium vs time (glass cell). Inner cylinder speed is 8.95 cm/s. The absence of lines in some regions indicates that the marker was not visible on the monitor screen during those time intervals.

the marker was further in, beyond the third layer, the marker was not observable on the videotape and therefore it must be assumed that it is in either the fourth or the fifth layer.

(d) The marker rarely makes its way to the top of the pile. However, it can be found more frequently within a few layers (4 or 5) from the top surface. For example, during a 15 min run, as is seen in Fig. 6, the marker never reaches the top surface. However, several times it got within a few layers from the top. It is possible that the marker would reach the top and fall back in the layers below while the marker was out of the scope of the camera.

D. Investigation of boundary effects on segregation process

The physical and geometrical characteristics of a boundary, such as friction and shape, have a very crucial influence on the dynamics of the flow. Since the segregation of larger particles in our experiments appears to be the byproduct of a convectivelike motion, and convection in granular materials is strongly affected by boundary conditions, we designed a new cell where the outer wall has an outward slant of 30° from the vertical. This cell is similar in spirit to the one described by Knight *et al.* [13]. The spacing between the inner cylinder and the outer cone increases as a function of height and as a result the number of layers present increases (the bottom of the cell still contains 5 layers). We placed a 2 mm marker at the bottom of the cell and performed experimental trials with the inner cylinder rotating at various speeds. The 2 mm marker rose to the top and moved in next to the inner cylinder and continued rotating on the top surface. The geometry affected the speed of the rise and not the segregation process itself.

IV. DISCUSSION

Particles in the Couette flow apparatus undergo movements in the vertical, radial, and azimuthal directions that are consistent with an overall convective flow that is vertically down at the inner wall and vertically up at the outer wall. All particles participate in the rotational motion about the axis of the cylinder. The closer a layer is to the inner wall the higher its azimuthal speed V_{θ}. There is, therefore, a radial velocity gradient or shear. In addition to the rotational motion the

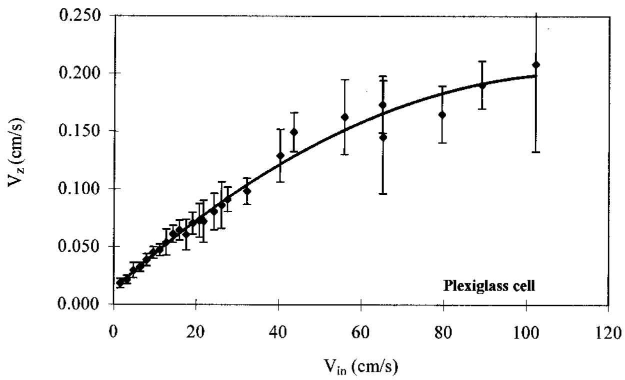

FIG. 7. Average vertical speed V_z of a 2 mm marker in a 1 mm glass medium vs inner cylinder speed in a plexiglass cell. The solid line represents a quadratic fit to the data.

particles show a pattern of up and down motion parallel to the cylinder's axis and a radial motion perpendicular to the axis. Individual particles show a combination of rolling and a slip-stick motion.

Measurements of the vertical speed of the 2 mm marker as a function of the inner cylinder speed in the glass cell, Fig. 3, and the data taken in a plexiglass cell, Fig. 7, confirm the existence of two distinct regimes with very different flow dynamics. The critical parameter that marks the transition from one region to another is the packing density.

In the first regime, the slow flow, the particles are in nearly continuous contact with each other during the shear process. One can identify comparable features between this flow and the laminar flow in ordinary fluids. Diffusive processes are superposed on the convective flow. In this regime the marker's vertical velocity is linearly dependent on the inner cylinder speed. Some of the scatter in Fig. 3 could be attributed to the finite particle size effect and the initial interlocking, which could take place at relatively high concentration and low speeds [15]. Data taken in a plexiglass cell in the first regime show less scatter and a smoother linear fit since the spacing between the inner and outer cylinder is 7 mm (hence accommodating seven layers). Experiments of Stephens and Bridgwater [20] also suggest an empirical linear relationship between the percolation velocity of smaller particles and the average shear rate $\dot{\gamma}$ (the shear rate in their experiments was time dependent). However, their experimental parameters and methods are very different from ours.

At high shear rates, the stable arching mechanism no longer supports the particles, and the dynamics is dominated by diffusion and particle collision. Particle collision in granular material is a source of energy loss and this loss depends on the coefficient of restitution e, which is known to decrease with increasing collisional velocities [21], and the coefficient of surface friction. This change in the flow dynamics, which is reflected in the change of dependence of V_z on V_{in} for $V_{\mathrm{in}} \gtrsim 20$ cm/s can be seen in Fig. 7. The deviation from a linear dependence for $V_{\mathrm{in}} \gtrsim 20$ cm/s can be attributed to two factors. First, the relative importance of interparticle collisions as a source of energy loss becomes greater at high speeds, reducing V_θ and, in turn, reducing the rate of growth of V_z with V_{in}. Second, the probability of the particles falling into holes below their level diminishes with increasing particle speed and this results in a lower rate of growth of V_z with V_{in} since, as discussed below, the fall of the medium through the holes increases convective motion. The increase in the size of the error bars suggests a regime analogous to the turbulent regime in an ordinary fluid. In the region where $V_{\mathrm{in}} \leqslant 9$ cm/s, we note that all particles, irrespective of their sizes, go through a characteristic convectivelike motion. They move up toward the top surface in the two layers adjacent to the outer, stationary wall and, once on the top surface, all particles move towards the inner cylinder wall. While the large particles remain on the top, the particles that make up the medium fall to the bottom or very near it as they move downward in the two layers adjacent to the inner, moving cylinder wall. The medium, in this range of speeds, must dilate in order to flow under shear, which means in order for the layer next to the wall to move the medium will be pushed radially outward and upward. Another effect of dilation, when a layer moves against another layer with a relative speed, is the generation of holes. The frequency of the generation of holes will be higher the closer one is to the inner wall since the particles are moving with higher speed. As a result the particles within the couple of layers adjacent to the outer stationary cylinder will experience a net upward push. The size of the holes is comparable to the particles of the medium and as a result a 1 mm particle has a larger probability of falling in these holes and moving downward. However, the larger particles have never been observed to fall below the top surface even though they spend their time entirely moving adjacent to the inner wall.

This model is consistent with our observations of the motion of large particles (2 and 3 mm), as well as the particles that compose the medium (1 mm). The larger particles placed at the bottom moved up to the top while in the few outer layers. We never observed a particle to rise while within the two layers adjacent to the inner wall. The large particles rise to the top surface and remain on the top, rotating with the top surface and in contact with the inner wall. The average vertical speeds of the 2 and 3 mm marker increases with the inner cylinder rotation speed, that is, they take a shorter time to reach the top. This can be explained by the fact that the frequency of hole generation increases with the rise of the rotation speed and, in turn, increases the speed of convective flow. The 3 mm marker rises with a higher speed than the 2 mm marker (see Table I). The difference could be caused by the fact that in some experimental runs the steady rise of the 2 mm particle was interrupted when the marker moved to the third layer (at heights between 1 and 1.5 cm) and its vertical motion was halted until it moved back again into the second layer. In addition the gravitational fall through the holes, which contributes to the frictional force, [9], occurs with a lower probability for the 3 mm marker since the hole sizes are on the average proportional to the diameter of the particles in the medium.

The 1 mm marker's motion is not as smooth and steady as the larger markers' specifically because the larger particles do have a much smaller chance of falling into the empty spaces. The 1 mm particles generally rise to the top using the two or three outer layers. On its way up, the marker falls a short distance from time to time. However, the frequency of hole generation diminishes as a particle moves away from the inner moving cylinder, and as a result the 1 mm marker experiences a net push upward while in the few outer layers. We have never observed the 1 mm marker rising while in the layer adjacent to the inner cylinder or the layer next to it. The fastest falls occur when the particle is in contact with the fifth (innermost) and at times the fourth layer.

V. CONCLUSION

This study probes into the fundamentals of particle dynamics in a Couette flow geometry. We have experimentally arrived at many of the mechanisms involved in the flow while a host of intriguing questions remain for further study. The first finding of our work was the ever present phenomenon of particle segregation. All particles larger than those of the medium rose to the top surface of the Couette cell when under shear and remained on the top surface over a wide range of inner cylinder speeds. Extensive measurements of the speed of the segregation were made using 2 and 3 mm markers in a 1 mm medium. In addition the dependence of the segregation on the wall material and geometry were checked using two different wall slants and wall materials. Segregation occurred in all cases, but the exact dependence of it on geometry and friction awaits further work.

The second major outcome of our work was establishing the convective nature of flow in the medium, which we believe is the mechanism driving the segregation process as well. We arrived at a convective mechanism by repeated measurements of the position of a single particle at a specific cylinder speed in the low velocity regime. It is not known how the convection is affected by the increase of the inner cylinder speed, in particular in the high velocity regime. In addition at this time we know very little about the shape and the number of the convective rolls. Although it is well known that the boundary conditions at the walls are important for creating convection, the role of the friction, the shape of the wall, and the precise nature of the interplay between the two is not understood for this experiment. A peculiar transition, similar to laminar to turbulent, was noted in our measurement of the segregation velocity versus inner cylinder speed. This transition was marked by a sudden increase in the standard deviation of the vertical velocity and a deviation from a linear dependence of the vertical velocity on inner cylinder speed. We have evidence that this transition is connected to the lowering of the packing density below the random loose packing limit where the stable arching mechanism no longer supports the particles, and the dynamics is dominated by diffusion and particle collision. However, the rate of change of the segregation speed as a function of the inner cylinder speed and its dependence on the collisional properties of the particles need further work. In summary we have experimental evidence of convection in the Couette flow geometry and our proposed model indicates that the segregation is a byproduct of the convection.

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