Onset of Instability in Sheared Gas Fluidized Beds

Eliano Apicella and Matteo D'Amore
Dept. of Chemical and Food Engineering, University of Salerno, Fisciano, Italy

Gabriel Tardos and Roberto Mauri
Dept. of Chemical Engineering, City College of City University of New York, New York, NY 10031

The idea behind this work is to use the stabilizing effect of shear to homogenize bubbling gas fluidized beds. Essentially, we argue that by increasing the shear we increase the particle diffusivity, therefore enhancing the tendency of the particles to distribute uniformly in the bed. Although similar effects are known to play important roles in the diffusion of particles suspended in viscous liquids at very low Reynolds number, in this work we present the first evidence that this effect might be relevant also when the suspending fluid is a gas.

Experimental Results

The experimental work was performed using a bed of heavy particles confined between two concentric cylinders, which were mounted on a distributor to allow fluidization (see Figure 1). The Couette-type fluidized bed had an outer radius of 7.62 cm and a 1.25 cm gap, while the bed heights ranged from 10.5 to 16.5 cm. The outer cylinder was kept stationary, while the inner cylinder was rotated by a variable speed motor with angular velocities ranging from 0 to 2.5 s^{-1}. In order to prevent any slip at the walls, sand paper was glued to the inner surfaces of the cylinders with a coarseness roughly equal to the particle size. Finally, as the inner cylinder was rotating, gas was pumped through the distributor, so that the bed was sheared and fluidized at the same time.

As the gas velocity v was increased at constant shear rate γ, a critical condition $v = v_c$ was reached at which bubbles started to appear. Despite the periodic behavior of bubbling fluidized beds, their state is denoted here as "unstable," just like Taylor vortices and Benard cells are instabilities with periodic characteristics (see Harris, 1996, and references therein). The minimum bubbling fluid velocity can be trivially determined visually, as bubbles can be easily seen bursting at the upper surface of the fluidized bed. More accurately, we also measured the differential pressure fluctuations between two pressure taps placed at the bottom and over the top of the bed, using a low-range, high-output pressure transducer. Then, following a similar procedure as in Alzahrani and Wali (1993) and Wayne et al. (1993), we defined the minimum bubbling critical velocity v_c as that corresponding to the appearance of clearly identifiable, broad peaks in the Fourier spectrum of the pressure fluctuations, signaling the existence of bubbles in the bed. The minimum bubbling critical velocity that was determined in this way was in excellent agreement with that determined visually.

First, we studied the behavior of a bed of 250–300 μm-size glass beads, as an example of the so-called group B powders, where short-range interparticle forces are small. As expected, in this case bubbles started to appear at the minimum fluidization velocity. The critical shear rate γ_c at the onset of bed instability for different heights h of the settled bed is represented in Figure 2 as a function of the difference $(v - v_{mf})$ between the fluid velocity and the minimum fluidization velocity ($v_{mf} = 9.0$ cm/s in this case). Our results show that the critical shear rate which needs to be applied to "homogenize" the bed increases linearly as we increase the gas

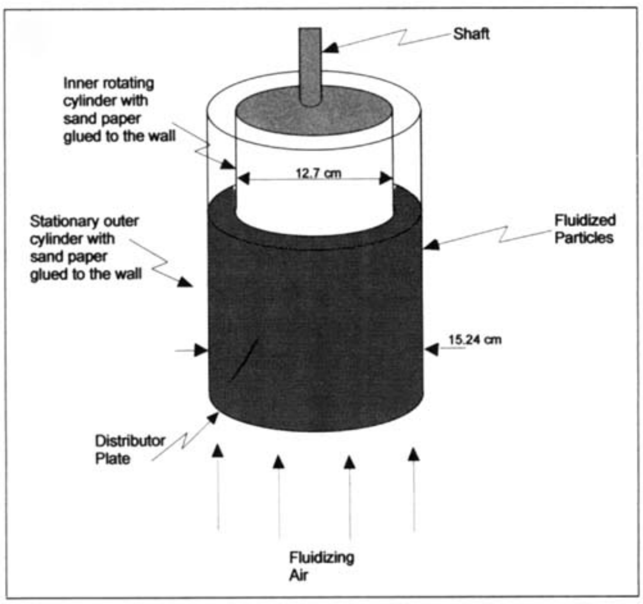

Figure 1. Couette fluidized bed.

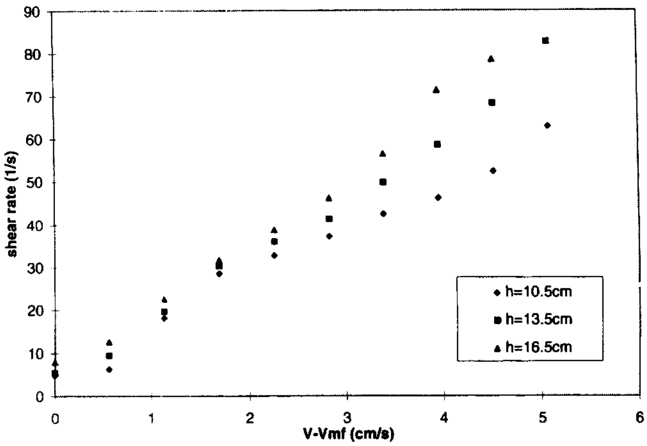

Figure 2. Shear rate γ_c as a function of the excess gas velocity $(v - v_{mf})$ at the onset of bubbling of a sheared fluidized bed using 250–350 μm glass beads particles.

Three sets of data refer to three different bed heights h.

velocity and, in addition, appears to be proportional to the bed height. Even at minimum fluidization the critical shear rate, albeit very small, was nonzero.

Next, we considered an example of the so-called group A powders, where short-range interparticle forces play an important role in determining a velocity of minimum bubbling in the absence of shear v_{mb} which is larger than v_{mf}. Using 100–300 μm-size sodium chloride particles with $v_{mf} = 2.8$ cm/s and $v_{mb} = 3.1$ cm/s, our results (plotted in Figure 3) show that the dependence of γ_c on $(v - v_{mf})$ is again linear; unlike the previous case, however, our sets of data for different bed heights now do not pass anywhere near the origin in agreement with our intuition, indicating that the shear has to overcome the additional effect of interparticle short-range forces.

These experimental results suggest that fluidized beds with gas velocities equal to v_{mb} can be homogenized only when

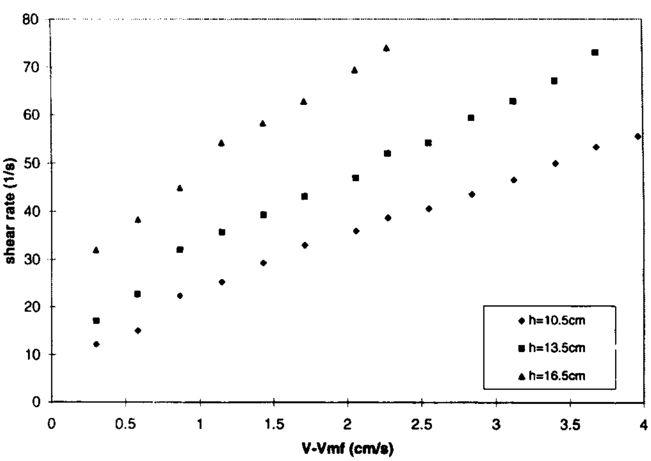

Figure 3. Shear rate γ_c as a function of the excess gas velocity $(v - v_{mf})$ at the onset of bubbling of a sheared fluidized bed using 100–300 μm sodium chloride particles.

Three sets of data refer to three different bed heights h.

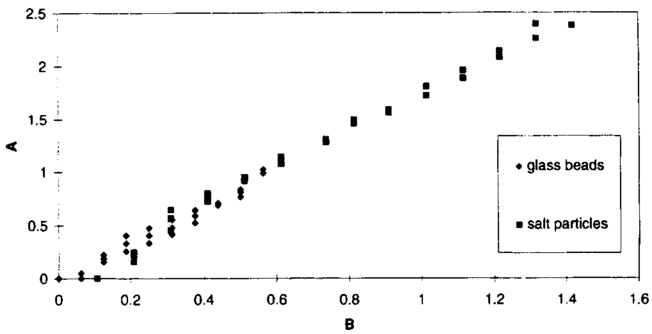

Figure 4. Shields number A as a function of the Stokes number B at the onset of bubbling.

the applied shear rates are larger than a critical value γ_{mb}, which depends on the bed height (γ_{mb} is the critical shear rate when $v_c = v_{mb}$). For the group B, powder used in the previous set of experiments γ_{mb}, although not zero, is very small. The results of Figures 2 and 3 are summarized in Figure 4, in terms of two nondimensional parameters A and B

$$A = \frac{(\gamma - \gamma_{mb})\delta^2}{v_{mf} h}; \quad B = \frac{v - v_{mf}}{v_{mf}}, \tag{1}$$

where δ is the gap of the Couette device. In the next section, we will see that A represents the ratio between shear and buoyancy and, therefore, can be interpreted as the Shields number, while B is the ratio between drag and buoyancy, and can be interpreted as a Stokes number. Clearly, Figure 4 indicates that all our experimental data collapse on a single curve, with A and B proportional to each other, and $\alpha = A/B$ equal to a constant

$$\alpha = \frac{(\gamma_c - \gamma_{mb})\delta^2}{(v_c - v_{mf})h} \approx 1.7. \tag{2}$$

The value of α appears to be independent of the type and size of the fluidized particles and of the height of the bed.

It should be stressed that in all our experiments the particle Reynolds number is of order one, that is, $Re = av/\nu = O(1)$, where a is the particle radius and ν the gas kinematic viscosity. In addition, treating the fluidized bed as an effective medium whose viscosity can be evaluated using the Ergun correlation, we can see that the critical shear rate required for the onset of Taylor instability was about 5 s^{-1}, which was well below the typical range of variation of γ (that is, from 10 to 100 s^{-1}). Consequently, it is easy to see that the size of the Taylor vortices typically exceeded the gap of the Couette device.

Interpretation of Experimental Results

In this section we describe a simple model to explain the experimental results described in the previous section. It is intended to be a tentative explanation which, although reasonable, at this stage is only a conjecture.

Since the stability of a fluidized bed increases with shear, it is reasonable to introduce a shear-induced "homogenizing" mechanism, that allows the particles to diffuse from regions of high concentrations to low. This shear-induced diffusion process will lead to a flux $J_s = -D(\phi)\nabla\phi/dz$, where the shear-induced diffusion coefficient $D(\phi)$ is dimensionally the product of the fluid velocity by a characteristic length. A similar effect arises in turbulent flows, where the transport of passive scalars can be described via a so-called eddy diffusivity, which in turn is proportional to the product of the mean fluid velocity by the size of a typical eddy. As the fluid flow has a random component, in this case clearly particle motion will be chaotic and the net effect will be diffusive even when particle trajectories coincide with fluid streamlines (that is, tracers are passive). On the contrary, in our case the diffusive or chaotic nature of the particle transport is not due to the turbulence of the flow field (in fact the Reynolds number is $O(1)$), but to the randomness of the particle interactions (that is, tracers are not passive). In other words, if we imagine following one particle along its trajectory, we would see it undergoing a random motion due to its collisions with other particles, and this motion can be described macroscopically as a diffusion process with a diffusion coefficient $D(\phi)$ which is proportional to the product of a typical particle velocity $\gamma\delta$ by a characteristic lengthscale of the particle motion. In general, we think that this characteristic length will be equal to the size of the Taylor vortices; however, since in our case the size of the Taylor vortices exceeded the gap of the Couette device, the characteristic length is set equal to δ, so that $D \propto \gamma\delta^2$, and $J_s = O(\gamma\delta^2\phi/h)$. This dispersion mechanism is in many ways similar to the shear-induced diffusion encountered at very small Reynolds numbers (Leighton and Acrivos, 1987a,b; Wang et al., 1996), but with a fundamental difference: at a very low Reynolds number, no characteristic length is available other than the particle radius, so that the effective diffusivity must be proportional to the product of the shear rate by the square of the particle radius. Note that in our dimensional analysis, the typical length in the vertical direction has been assumed to be equal to the height of the settled bed h instead of its height during fluidization. In fact, applying the Richardson-Zaki equation (Yates, 1996), it is easy to see that the change in bed height due to fluidization is only few percent of its unsettled value and was undetectable in our experiments.

Now, at the onset of instability, the shear-induced diffusion process will balance the combined effect of convection and short-range particle interactions. In fact, as the fluid flow is increased above its critical value, particles will tend to be convected upward, leading to a nonhomogeneous concentration profile which, in turn, will be balanced by downward shear induced diffusion. The upward excess flux of particles is the difference between drag and gravity, and leads to the buoyancy-driven flux $J_b = \phi(v - v_{mf})$, since v_{mf} is the fluid velocity required to support the bed weight. In addition, we should also consider the effects of short-range particle interactions, which are typically due to adhesion; they are independent of both shear rate and gas velocity, and appear to play a significant role only when the gas velocity is smaller than v_{mb} (Rietema, 1991; Lim et al., 1995). Since short-range forces appear to counterbalance shear-induced diffusion at minimum bubbling conditions, we expect that they will lead to a flux $J_f = O(\gamma_{mb}\delta^2\phi/h)$, independent of v, provided that v is larger than v_{mb}. In essence, that means that only a ratio $(\gamma - \gamma_{mb})/\gamma_c$ of the total shear rate γ can be applied to homogenize the bed, while the remaining γ_{mb}/γ ratio will be used to compensate for the interparticle short-range forces.

Finally, since the total particle flux $J = J_b + J_s + J_f$ is equal to zero, we find that $(v - v_{mf})h \propto (\gamma - \gamma_{mb})\delta^2$, that is, $A \propto B$, in agreement with the results shown in Figures 2, 3, and 4.

Although this result is probably not true in general (for example, for much larger gaps we expect a more complex $A - B$ dependence), we believe that it is nevertheless applicable to a wide variety of powders.

Conclusions and Discussion

In this work we presented a series of experimental measurements showing that a bubbling fluidized bed can be stabilized by shear. The shear rate that needs to be applied to homogenize the bed appears to be proportional to the gas velocity and to the bed height. In addition, the ratio α between buoyancy- and shear-induced velocities at the onset of instability $(v_c - v_{mf})$ and $(\gamma_c - \gamma_{mb})\delta^2/h$, respectively, was found to be a constant approximately equal to 1.7, independent of the type and size of the fluidized particles and of the height of the bed. These experimental findings are explained qualitatively via a simple model in which, without specifying why bubbling occurs, we have assumed that it starts as soon as the fluid flow exceeds a critical value with the downward shear-induced diffusion flux balancing the upward convective excess flux. This model, although very crude and in need of further work, is in qualitative agreement with the analyses of many investigators (Jackson, 1963; Garg and Pritchett, 1975; Homsy et al., 1980; Needham and Merkin, 1983, 1986; Foscolo and Gibilaro, 1984, 1986, 1987; Batchelor, 1988; Harris and Crighton, 1994; Anderson et al., 1995; Harris, 1996), who predicted the onset of instability in fluidized beds based purely on hydrodynamic considerations. Far from considering this model anything more than a conjecture, we hope that it will stimulate further discussions and, especially, further experimental works.

Among the experiments that remain to be done to verify the proposed model of shear fluidized beds, we intend first to measure the particle velocity field and the bed density profile. In fact, our model predicts the existence of eddies of the same size as the Couette gap, and by tracing the motion of a few tracer particles we could verify the validity of this assumption. In addition, as a concentration gradient is required according to our model to counterbalance the excess particle flux in the bed, detecting a nonuniform density profile would be another experimental validation of our model. Here, we want to make two observations. First, in the absence of shear our model predicts that no density gradient is present in the bed, in agreement with experimental measurements (Lim et al., 1995); the homogeneity of the bed is consistent with the fact that the velocity at minimum fluidization does not depend on bed height. The second observation is that in the presence of shear, Figures 2 and 3 show that the minimum bubbling velocity strongly depends on bed height, indicating that the bed is not uniform. However, a simple dimensional analysis equating diffusive and buoyancy-driven fluxes shows that $\nabla\phi/\phi \sim (v - v_{mf})/(\gamma\delta^2) \sim 10^{-2}$ cm^{-1}, so that we expect the typical concentration gradient to be quite small. A similar behavior was observed in the resuspension case studied by Acrivos et al. (1993) for very low Reynolds numbers.

Furture work should include studying the dependence of the Couette gap on our results. In fact, our model predicts that whenever the Couette gap is smaller than the size of the Taylor vortices, the dependence of the Shield number on the Stokes number will be linear. However, for larger gaps, we expect that the strength of the Taylor vortices will play an important role, and the critical shear rate will no longer be proportional to the excess particle flux.

Finally, we intend to apply this phenomenon to different processes with industrial applications, such as the pneumatic transport of particles on inclined fluidized chutes.

Acknowledgments

R. M. was supported in part by grant No. DE-FG02-90ER14139-0006 from the Office of Energy Research of the Dept. of Energy. The authors wish to thank one of the referees for his constructive and thoughtful comments.

Literature Cited

Acrivos, A., G. K. Batchelor, E. J. Hinch, D. L. Koch, and R. Mauri, "Longitudinal Shear-Induced Diffusion of Spheres in a Dilute Suspension," *J. Fluid Mech.*, **240**, 651 (1992).

Acrivos, A., R. Mauri, and X. Fan, "Shear-Induced Resuspension in a Couette Device," *Int. J. Multiphase Flow*, **19**, 797 (1993).

Anderson, K., S. Sundaresan, and R. Jackson, "Instabilities and the Formation of Bubbles in Fluidized Beds," *J. Fluid Mech.*, **303**, 327 (1995).

Alzahrani, A. A., and M. M. N. Wali, "A Study of Pressure Drop Fluctuations in a Gas-Solids Fluidized Bed," *Powder Tech.*, **76**, 185 (1993).

Batchelor, G. K., "A New Theory on the Instability of a Uniform Fluidized Bed," *J. Fluid Mech.*, **193**, 75 (1988).

Foscolo, P. U., and L. G. Gibilaro, "A Fully Predictive Criterion for the Transition between Particulate and Aggregate Fluidization," *Chem. Eng. Sci.*, **39**, 1667 (1984).

Foscolo, P. U., and L. G. Gibilaro, "The Influence of Gravity on the Stability of Fluidized Beds," *Chem. Eng. Sci.*, **41**, 2438 (1986).

Foscolo, P. U., and L. G. Gibilaro, "Fluid Dynamic Stability of Fluidized Suspensions: The Particle Bed Model," *Chem. Eng. Sci.*, **42**, 1489 (1987).

Garg, S. K., and J. W. Pritchett, "Dynamics of Gas-Fluidized Beds," *J. Appl. Phys.*, **46**, 4493 (1975).

Harris, S. E., and D. G. Crighton, "Solitons, Solitary Waves and Voidage Disturbances in Gas-Fluidized Beds," *J. Fluid Mech.*, **266**, 243 (1994).

Harris, S. E., "The Growth of Periodic Waves in Gas-Fluidized Beds," *J. Fluid Mech.*, **325**, 261 (1996).

Jackson, R., "The Mechanics of Fluidized Beds: I and II," *Trans. Instn. Chem. Engrs.*, **41**, 13 (1963).

Leighton, D., and A. Acrivos, "Measurement of Shear-Induced Self-Diffusion in Concentrated Suspensions of Aspheres," *J. Fluid Mech.*, **177**, 109 (1987a).

Leighton, D., and A. Acrivos, "The Shear-Induced Migration of Particles in Concentrated Suspensions," *J. Fluid Mech.*, **181**, 415 (1987b).

Lim, K. S., J. X. Zhu, and J. R. Grace, "Hydrodynamics of Gas-Solid Fluidization," *Int. J. Multiphase Flow*, **21**, 141 (1995).

Needham, D. J., and J. H. Merkin, "The Propagation of a Voidage Disturbance in a Uniformly Fluidized Bed," *J. Fluid Mech.*, **131**, 427 (1983).

Needham, D. J., and J. H. Merkin, "The Existence and Stability of Quasi-Steady Periodic Voidage Waves in a Fluidized Bed," *Z. Angew. Math. Phys.*, **37**, 322 (1986).

Rietema, K., *The Dynamics of Fine Powders*, Elsevier, London (1991).

Wang, Y. G., R. Mauri, and A. Acrivos, "The Transverse Shear-Induced Liquid and Particle Tracer Diffusivities of a Dilute Suspension of Spheres Undergoing a Simple Shear Flow," *J. Fluid Mech.*, **327**, 255 (1996).

Wayne, W. S., N. N. Clark, M. Gautam, and R. Turton, "Pressure Field Measurement in a Bubbling Fluidized Bed," *Powder Tech.*, **76**, 331 (1993).

Yates, J. G., "Effects of Temperature and Pressure on Gas-Solid Fluidization," *Chem. Eng. Sci.*, **51**, 167 (1996).

Manuscript received July 5, 1996, and revision received Dec. 4, 1996.