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CONCENTRATION AND VELOCITY GRADIENTS IN FLUIDIZED BEDS

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Introduction

Sedimenting and fluidized beds are widely used in industry for separation process and enhanced heat transfer. As is commonly the case, widespread use does not mean there are no interesting, fundamental questions. Detailed understanding of these beds requires complete understanding of multi-particle, long-range hydrodynamic interactions as a function of concentration. Such problems are still minimally tractable.

It was recently recognized [5] that the stability of fluidized beds cannot be explained by the standard "classical" model. It was commonly accepted that sedementing and fluidized beds have uniform concentration profiles. Recent experiments show that concentration and velocities vary significantly on multi-particle length scales [1,2,3,6,7]. Another experiment [8] explicitly showed that an initially uniform concentration profile in a sedementing bed is unstable. This instability can be understood in light of two facts. It is empirically known that sedimentation velocity decreases with increasing particle concentration,

$$(1)\ V_{SED} = V_0 (1-\phi)^k, k > 0.$$

The value of k depends on the interparticle potential [4] and is typically between 5 to 6. Creating a stable bed would then seem to require maintaining the exactly appropriate flow velocity for a given concentration. Correlated fluctuations in particle number, and hence density, were recently discovered [6]. These denser regions sink faster than the surrounding particles while the less dense regions rise. Since there are more particles in the sinking regions than the rising regions, the bed collapses, unless another mechanism exists to counter the collapse. Segre [5] recently made detailed measurements on a stable bed. His measurements indicate that both the concentration and the sedimentation velocity is height dependent. This height dependence provides the mechanism to stabilize the bed.

Procedure

In this work we focus on the height dependence of particle concentration, average velocity components, fluctuations in these velocities and, with the flow turned off, the sedimentation velocity. The latter quantities are measured using Particle Imaging Velocimetry (PIV). The PIV technique uses a 1-megapixel camera to capture two time-displaced images of particles in the bed. The depth of field of the imaging system is approximately 0.5 cm. The camera images a region with characteristic length of 2.6 cm for the small particles and 4.7 cm. for the large particles. The local direction of particle flow is determined by calculating the correlation function for sub-regions of 32 X 32 pixels. The velocity vector map is created from this correlation function using the time between images (we use 15 to 30 ms). The software is sensitive variations of 1/64th of a pixel. We produce velocity maps at various heights, each consisting of 3844 velocities. We break this map into three vertical zones for increased height information.

The concentration profile is measured using an expanded (1 cm diameter) linearly polarized HeNe Laser incident on the fluidized bed. A COHU camera (gamma=1, AGC off) with a lens and a polarizer images the transmitted linearly polarized light to minimize the effects of multiply scattered light. The intensity profile (640 X 480 pixels) is well described by a Gaussian fit and the height of the Gaussian is used to characterize the concentration. This value is compared to the heights found for known concentrations. The sedimentation velocity is estimated using by imaging a region near the bottom of the bed and using PIV to measure the velocity as a function of time. With a nearly uniform concentration profile, the time can be converted to height information.

The stable fluidized beds are made from large pseudo-monodisperse particles (silica spheres with radii (250-300) microns and (425-500) microns) dispersed in a glycerin/water mix. The Peclet number is sufficiently large that Brownian motion of the particles can be ignored and the Reynolds number sufficiently small that particle inertia is negligible. A packed particle bed is used to randomize and disperse the flowing fluid introduced by a peristaltic pump. The bed itself is a rectangular glass cell 8 cm wide (x), 0.8 cm deep and a height of 30.5 cm (z). The depth of field of the camera is approximately 0.5 cm so depth information is averaged. Over flow fluid is returned to the reservoir making a closed loop system. In these experiments the particles form a sediment approximately 5.7 cm high with the pump off and expand to 22 cm with the pump on. For the smaller particles the pump velocity is .5 mm/s and 1.1 mm/s for the large particles. At this concentration the bed has a very well defined “top” where particle concentration rapidly drops to zero.

Results

Figure 1 A and B show the average velocity in the x and z direction and their RMS fluctuations (F_{vx} and F_{vy}) for a stable bed for the two particle sizes. The two beds have the same average particle concentration. The stability of the bed is clearly shown by the near zero average velocities. The velocity fluctuations are largest near the bottom of the bed (which results in a larger uncertainty for the velocity values) and vanish near the top. The particles at the top of the bed are stationary. The RMS velocity fluctuations are well fit by a power law.

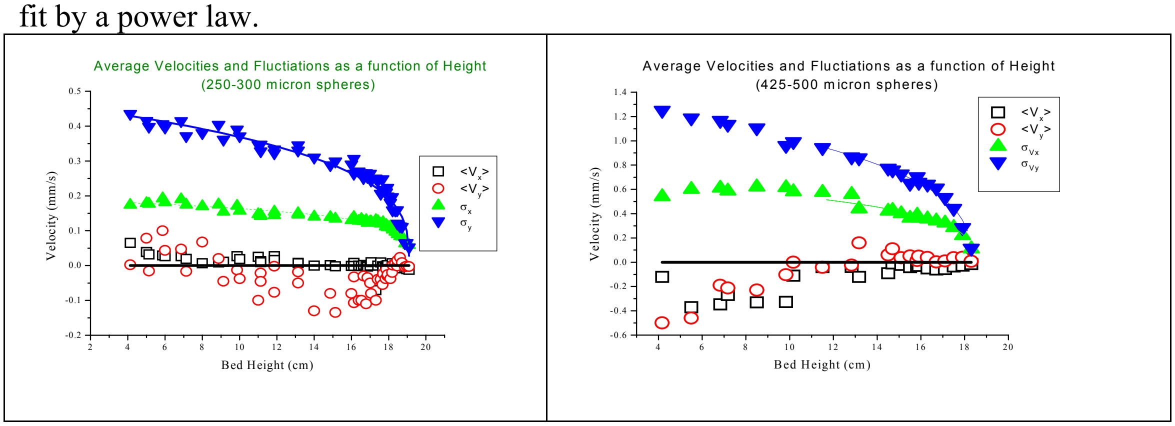

Figure 1. Average Velocity (open red circles <V_z>, open black boxes <V_x>) and RMS values of velocity fluctuations (filled green up triangles RMS(V_x), filled blue down triangles RMS(V_z). Fluctuations are well fit by a power law with an exponent near 1/3.

Figure 2 shows the sedimentation velocity for the two beds. The sedimentation velocity is less than the pump velocity at all heights (except at the top of the column). An “excess” velocity is defined as $V_{ex} = V_{pump} - V_{sed}$. Figure 3 shows the concentration profile for the two beds (Figure 4). The correlation length is determined from the velocity maps and the height dependence shown in Figure 4.

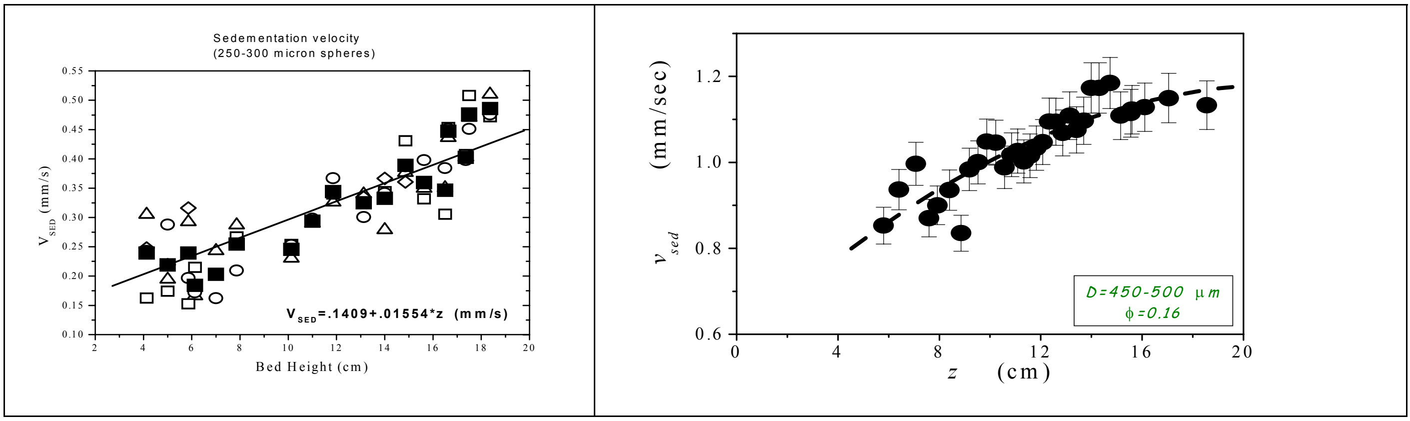

Figure 2. Sedimentation velocity as a function of height.

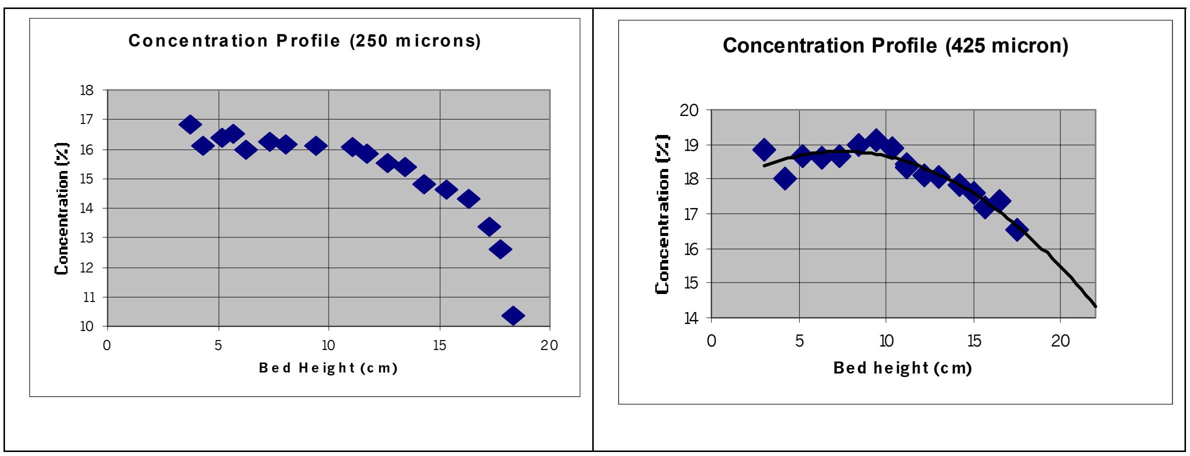

Figure 3.Concentration as a function of height for the two particle sizes.

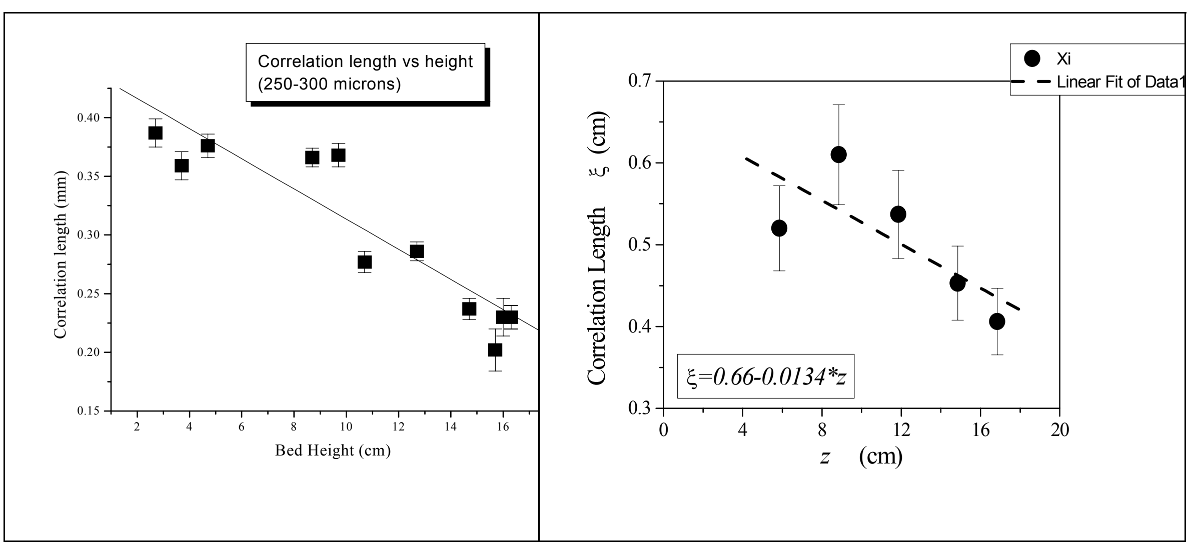

Figure 4. Correlation Lengths for two particle sizes.

Conclusion

Segre [5] developed a flux balance equation

$$2.\quad \partial(\phi\, v_{ex}) \big/ \partial z = -0.8\,\sigma_{vz}\sqrt{S(\phi)\phi\, a^{3} \big/ \xi^{5}}$$

where a, ξ, ϕ are the particle radius, correlation length, and concentration respectively. $S(\phi)$ corrects for excluded volume effects using the Carnahan-Starling equation for hard spheres [4]. Integrating EQ (2) gives the result in Figure 5 in which the integral of the two terms (flux) and their sum is shown. As predicted the sum is near zero.

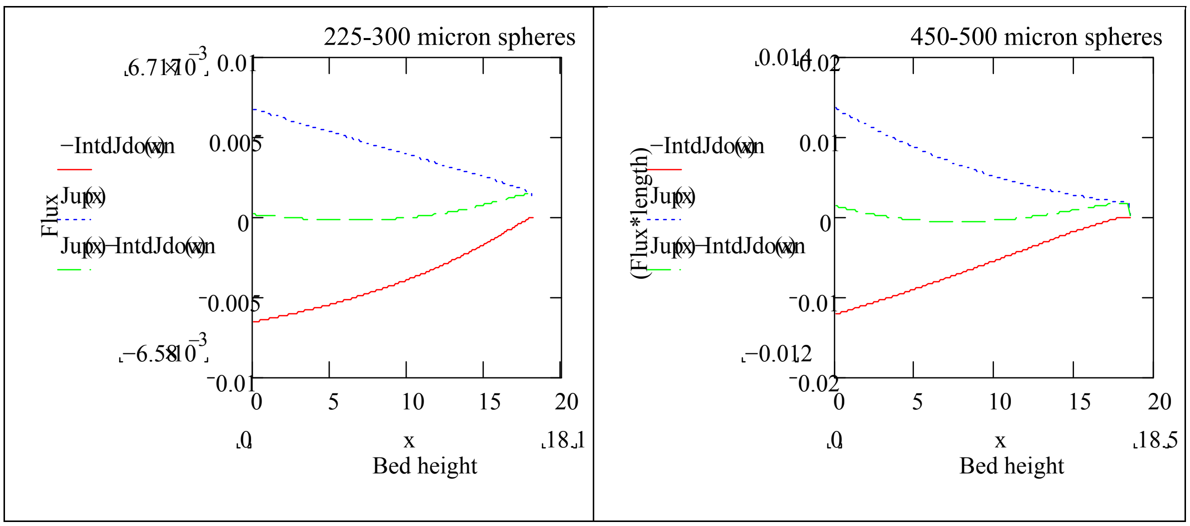

Figure 5. The blue curves are the upward flux due to the excess velocity. The red curve is the downward flux due to concentration fluctuations. The green curve is the sum of the two curves and is near zero over the entire bed height.

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