Aggregation and sedimentation in gas-fluidized beds of cohesive powders

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We present measurements on the settling velocity of gas-fluidized beds of fine cohesive powders. In the solidlike regime (solid volume fraction $\phi > \phi_c$) particles are static, sustained by enduring contacts. The settling is hindered by interparticle contacts and is a very slow process. In the fluidlike regime ($\phi < \phi_c$) permanent contacts no longer exist, and the bed displays a diffusive dynamics. The interparticle adhesive force leads to the formation of particle aggregates, and for this reason the sedimentation velocity exceeds the predicted value by empirical or theoretical laws on the settling of individual particles. We use an extension of the Richardson-Zaki empirical law for the settling of aggregates in the fluidlike regime to fit the experimental data. Aggregates are characterized by the number of aggregated particles N and by an effective radius R. The trend followed by these parameters with particle size is confirmed by direct visualization of the aggregates, and shows that cohesive effects become important when the adhesion force between particles is above particle weight. Results show that aggregates form open structures with a fractal dimension close to the predicted one in the diffusion-limited-aggregation model ($D = 2.5$).

I. INTRODUCTION

Gas-fluidized beds are widely used in industry, and their properties have been the subject of research for some decades. An important issue is to understand the settling rate of the particles when the fluidizing gas is suddenly stopped. The problem is analogous to that of the sedimentation of suspensions of solid particles in a liquid, which, in spite of having a long and well-deserved history for its ubiquitous applications [1], is not yet well understood. For a multiparticle system at low solid volume fractions (ϕ), long ranged hydrodynamic interactions hinder sedimentation [2]. At higher values of ϕ the presence of a fluid backflow arising from the sedimenting particles, interparticle collisions, and crowding become increasingly important [3]. The relationship between the settling velocity in sedimentation v_s and the solid volume fraction ϕ for a homogeneous gas-fluidized powder of noncohesive spheres was well described by the phenomenological Richardson-Zaki law [4]

$$\frac{v_s}{v_{p0}} = (1 - \phi)^n. \tag{1}$$

Here v_{p0} is the Stokes settling velocity of a single particle, $v_{p0} = (2/9)(\rho_p - \rho_f) a^2 g / \mu$ in the laminar regime, where ρ_p is the particle density, ρ_f is the gas density, g is the gravity field, a is the particle radius, μ is the viscosity of the gas, and n is a parameter of order 5 in the small Reynolds number limit. Buscall *et al.* [5] reported on measurements of the mean fall velocity of sedimenting polystyrene spheres in water in a small Reynolds number range over the whole range of values of ϕ which fitted to the Richardson-Zaki law for $n = 5.5$. Theoretical considerations by Batchelor [6] led to $v_s/v_{p0} = 1 - 5.6\phi$ [7] for very diluted suspensions of non-Brownian monodisperse hard spheres in the limit of small Reynolds numbers. Thus the sedimentation velocity predicted by Eq. (1) conformed with the dilute limit of Batchelor for $n = 5.6$. The simplicity of the Richardson-Zaki equation, although satisfying from a practical point of view,

lacked any theoretical justification at high values of ϕ. Mills and Snabre [8] theoretically derived the settling velocity for a system of concentrated noncohesive spheres from the energy balance during the sedimentation process. They used mean field and scaling arguments to arrive at the expression

$$\frac{v_s}{v_{p0}} = \frac{1 - \phi}{1 + k\phi/(1 - \phi)^3} \tag{2}$$

and reported on excellent agreement with experimental data by choosing the parameter $k = 4.6$ to match Eq. (2) in the diluted limit [$v_s/v_{p0} = 1 - (k+1)\phi$] to Batchelor's result. Equation (2) yields, in the relevant range $\phi < -0.6$, results almost identical to those of the empirical Richardson-Zaki equation.

When the particle size is smaller than some critical value, the gravity is dominated by interparticle forces. This makes an understanding of the settling process more complicated [22]. In situations dealing with the flow of the bulk powder, it is generally observed that the tendency of particles to aggregate leads to a substantial departure from the behavior of free-flowing particulate systems [9–11]. From numerical simulations and experiments Nase *et al.* [11] found that the static angle of repose of a granular heap did not depend on the particle size if the particle weight W exceeded the interparticle adhesion force F_a, but increased markedly as $F_a/W = \mathrm{Bo}_g$ was increased above 1. As with the static heap angle, a sharp decrease was observed to occur in the discharge rate through a hopper when Bo_g was increased above 1. In that work cohesion arose from capillary forces, and the nondimensional number Bo_g was reminiscent of the Bond number in fluid mechanics. For this reason it was referred to as the granular Bond number [11]. In the case of dry fine particles (particle size < -30 μm) the van der Waals attractive force is dominant and may exceed the particle weight [14,15] by several orders of magnitude. Numerical simulations and experiments [12] revealed the important role of the ratio of this force to particle weight (for which, hereafter, we

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