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An investigation on the mechanics of homogeneous expansion in gas-fluidized beds

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HIGHLIGHTS

- We model the stable expansion in gas-fluidized beds of different diameters.
- We solve the model and analyze the results using the Richardson and Zaki equation.
- We study the role of enduring particle–particle contacts in uniform gas-fluidized beds.
- We study the role of wall friction in uniform gas-fluidized beds.
- We conduct fluidization/defluidization experiments to validate our theoretical results.

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ABSTRACT

The Richardson and Zaki (1954, Sedimentation and fluidization. *Trans. Inst. Chem. Eng.* 32, pp. 35–53.) equation has been used extensively to investigate the expansion profiles of homogeneous gas-fluidized beds. The experimental value of the parameter n appearing in the equation indicates how significantly interparticle forces affect the expansion of these beds, revealing the relative importance of these forces with respect to the fluid dynamic ones. In this work, we modeled the stable expansion of gas-fluidized beds of different diameter, accounting for enduring contacts among particles and wall effects. We solved the model numerically to obtain the bed expansion profiles, back-calculating from them the values of the parameter n. For all the cases considered, we observed that the values of n are higher than those obtained by purely fluid dynamic correlations, such as those advanced by Richardson and Zaki, and Rowe (1987, A convenient empirical equation for estimation of the Richardson and Zaki exponent. *Chem. Eng. Sci.* 42, pp. 2795.). This effect was more pronounced in beds of smaller diameter. To validate our model, we carried out fluidization and defluidization experiments, analyzing the results by means of the Richardson and Zaki equation. We obtained a reasonable agreement between numerical and experimental findings; this suggests that enduring contacts among particles, which are manifestations of cohesiveness, affect homogeneous bed expansion. This effect is amplified by wall friction.

1. Introduction

Gas-fluidized beds generally exhibit heterogeneous structure, with rising pockets of gas named *bubbles*; liquid-fluidized beds, conversely, usually maintain a smooth appearance, expanding progressively as the fluid flow rate is increased. These two types of fluidization behaviors are respectively termed *aggregative or bubbling* (for gas-fluidized beds) and *particulate or homogeneous* (for liquid-fluidized beds). Although gas-fluidized beds generally exhibit aggregative fluidization, small particles with low density fluidized by gas display an interval of smooth expansion when the flow rate of fluid exceeds the minimum fluidization value (Tsinontides and Jackson, 1993). Particles with this stable behavior are classified by Geldart (1973) as Group A powders.

The physical origin of the stable behavior of Group A powders has been studied by several researchers. Some ascribed the stability of uniform suspensions to the effect of interparticle forces, while others sought for a purely fluid dynamic explanation. Jackson (1963) carried out a fluid dynamic stability analysis, but was unable to predict the stable behavior of gas-fluidized beds of fine materials. Also Garg and Pritchett (1975) investigated the dynamics of gas-fluidized beds theoretically, reporting that stability can be predicted by adding to the particle linear momentum balance equation a fluid dynamic force proportional to the spatial

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gradient of the fluid volume fraction. Foscolo and Gibilaro (1984) derived a stability criterion based on fluid dynamic arguments, resorting to the stability theory of Wallis (1969), to show that stability depends on the relative magnitude of the kinematic and dynamic waves that propagate in the bed (Mazzei et al., 2006; Mazzei, 2008). Similarly to Garg and Pritchett (1975), they reported that the force acting on the particles (in particular the drag component), present in the particle linear momentum balance equation, should contain an additional term proportional to the spatial gradient of the bed void fraction. Batchelor (1988) held a view which is similar in part to that of Foscolo and Gibilaro (1984). He proposed a predictive criterion for stability based on fluid dynamic considerations. But he did not support the idea that stability is a result of the dependence of the drag force on the void fraction gradient, as Foscolo and Gibilaro (1984) maintained; he showed instead that stability can arise from random fluctuations in the particle velocity.

Reitema (1973) and Mutsers and Reitema (1977), conversely, adopted the stability criterion of Wallis (1969) to show that the stable behavior observed in Group A powders may be attributed to the cohesive forces among particles. Their experiments show that when a uniform gas-fluidized bed is tilted over a horizontal axis, it remains stable until a critical tilting angle is reached, and at this angle the bed surface suddenly shears off. This observation demonstrates that uniform gas-fluidized beds maintain a mechanical structure that is caused by sustained contacts among particles. Mutsers and Reitema (1977) further argued that, if the stability of gas-fluidized beds is due to fluid dynamic forces, the voidage at minimum bubbling should depend on the ratio g/μ_g^2; conversely, if the stability is due to a network of interparticle contacts, it should depend on g/μ_g. Their experimental results showed that the latter holds, validating their claim that stability results from the action of interparticle forces.

Tsinontides and Jackson (1993) also investigated the mechanism of stabilization of gas-fluidized particles. They carried out fluidization and defluidization experiments of fine powders about complete cycles, from zero gas flow rate up to flow rates where bubbles start appearing in the bed and then back to zero. They measured the bed depth and pressure drop at each stage, determining the solid volume fraction profiles by employing a high-resolution gamma-ray densitometer. Their results revealed the presence of yield stress throughout the range of stable behavior. They thus concluded that the stability of gas-fluidized particles is due to the presence of particle–particle contact forces.

While attempting to explain the physical origin of stability in gas-fluidized beds, Fortes et al. (1998) used a theoretical approach to show that the stability of these systems has two distinct origins: one that is fluid dynamic, arising from the interactions between the solid and fluid phases, and one that is not, arising from interparticle forces. They proposed a mechanistic description for the latter, regarded as a stabilizing agent of fluidization, showing that clustering and particle dispersion in suspensions result from the competition between interparticle and fluid dynamic forces.

While the arguments among researchers on the physical origin of the stable behavior of gas-fluidized beds continue, some pertinent questions about these systems arise. Do homogeneous gas-fluidized beds consist of particles that float freely without interacting? Furthermore, if we deny the existence of particle–particle contact forces in these beds, how do we explain with fluid dynamic considerations alone the presence of particle interactions that often result in the formation of clusters? Valverde et al. (2003b) sought to answer these probing questions in their experimental work on the dynamics of gas-fluidized beds. They reported that the interval of stability observed in gas-fluidized Group A particles has two regimes, one with *'solid-like'* and another with *'fluid-like'* behavior. Castellanos (2005) examined the distinctive features of these regimes in the fluidization–defluidization experiments of xerographic toner particles. He reported that the solid-like regime is characterized by the existence of a network of permanent particle–particle contacts that stabilizes the bed against small perturbations. In this regime, the bed behaves like a weak solid with non-vanishing compressive and tensile yield stress. In the fluid-like regime, conversely, particle contacts are absent and the bed behaves like a low-viscosity liquid whose upper surface remains horizontal when tilted. These observations strengthen the idea that the stability of gas-fluidized beds may have two distinct origins: one purely fluid dynamic and one arising from particle contact forces.

In this work, we attempt to provide further insight into the stable behavior of homogeneous gas-fluidized beds. We believe that the effect of cohesiveness in these systems is reflected by the presence of enduring contacts among particles. Such contacts are characteristic of homogeneous gas-fluidized beds in the solid-like regime; therefore, we focused our analysis primarily on this regime. We carried out fluidization and defluidization experiments, analyzing the results by means of the Richardson and Zaki (1954) equation. We solved the one-dimensional linear momentum balance equations of Jackson (2000) for the fluid and solid phases, accounting for enduring contacts among particles, relating the numerical predictions of the model to our experimental findings. Now, to begin, we review the Richardson and Zaki equation, discussing on its ability to predict the expansion profiles of gas-fluidized beds.

2. Richardson & Zaki equation and homogeneous expansion of gas-fluidized powders

Richardson and Zaki (1954) advanced an empirical relationship between the sedimentation velocity u of monodisperse particles in a liquid and the void fraction ε of the dispersion. The equation reads

$$u = u_t \varepsilon^n \tag{1}$$

where n is an empirical parameter which depends on the free fall particle Reynolds number Re_t, and u_t is the unhindered terminal settling velocity of the particles. Several correlations have been proposed for determining the value of n. In particular, we report the empirical relationship proposed by Rowe (1987), which we used in this work

$$n(Re_t) = \frac{A + B \times 0.175 Re_t^{3/4}}{1 + 0.175 Re_t^{3/4}} \tag{2}$$

Here A and B are the values ascribed to n in the limits of viscous and inertial regimes, respectively. Richardson and Zaki (1954) take A and B to be equal to 4.65 and 2.39, respectively; Rowe (1987) employs the values of 4.70 and 2.35, while Khan and Richardson (1989) and Gibiliaro (2001) use 4.80 and 2.40, respectively. The unhindered terminal settling velocity u_t, on the other hand, can be obtained in the creeping flow regime using the well-known Stokes equation

$$u_t = \frac{(\rho_p - \rho_f) g d_p^2}{18 \mu_f} \tag{3}$$

Here μ_f and ρ_f are the viscosity and density of the fluid, respectively, d_p and ρ_p are the particle diameter and density, respectively, and g is the gravitational acceleration.

The Richardson and Zaki (1954) equation and the correlations proposed for estimating the exponent n are found to hold for liquid-fluidized systems, where they are very accurate in providing an excellent account of the expansion profiles of such systems. But questions were raised regarding the applicability of this correlation