Homogeneous gas fluidization: kinematic and dynamic wave velocities, particle mobility and apparent suspension viscosity

K. Gallucci and L.G. Gibilaro
Dipartimento di Chimica, Ingegneria Chimica e Materiali, Università di L'Aquila, Monteluco di Roio, 67040 L'Aquila, Italy

Homogeneous fluidization-quality of gas fluidized beds has received little attention in the research literature but has grown in importance in recent years, in part as a result of the observed behaviour of fluidized nanoparticle agglomerates in investigations into processing technologies for dealing with large quantities of these materials for numerous state-of-the-art applications. These agglomerates assume diameters which correspond to conventional fluidized bed inventories, but are of very high porosity and correspondingly very low density; they have been found to fluidize homogeneously with ambient air, displaying expansion characteristics in good quantitative accord with the Richardson-Zaki law. This behaviour turns out to be good agreement with predictions of a fluid-dynamic model for the fluidized state (P U Foscolo and L G Gibilaro 1987. Fluid dynamic stability of fluidized suspensions: the Particle Bed Model. Chemical Engineering Science 42. 1489; L G Gibilaro 2001. Fluidization-Dynamics, Butterworth Heinemann, Oxford), which provides a theoretical map for fluidization of any particle species by any fluid, thereby generalising the empirical Geldart map for fluidization by ambient air, and contains a region of fully homogeneous behaviour into which most nanoparticle agglomerates fall. Ambient air-fluidized particles of low density, having diameters of 1 mm or even more, are predicted, and have been found, to lead to expansion in a fully homogeneous manner: for example, expanded polymer particles, which can have densities of around 10 kg/m3, which is even lower than that of reported nanoparticle agglomerates. There exists therefore a considerable range of particle species for which homogeneous gas-fluidization can occur.

Homogeneous fluidization-quality may be characterised in terms of the velocities of kinematic and dynamic particle-concentration waves, the 'bulk mobility' of the particles and the apparent viscosity of the suspension. The bulk mobility parameter was first proposed by Batchelor (1988. A new theory for the instability of a uniform fluidized bed. Journal of Fluid Mechanics 183. 75), defined in terms of the small change in particle velocity brought about as a result of a small applied force. It may be readily predicted by means of the Particle Bed Model, and may be used to explain the observed differences between gas and liquid homogeneous fluidization: tightly held together gas-fluidized suspensions and considerable random particle motion for liquid fluidization (L.G. Gibilaro and P.U. Foscolo 2001. Letter to the editor. AIChE Journal 47. 2846). It would also appear to be closely linked to the concept of an apparent suspension viscosity, a simple inverse proportional relation existing between these two parameters for the limiting case of a single particle swept by a Newtonian fluid under low Reynolds number conditions. This relation is exploited below in the development of a predictive relation for apparent viscosity of a fluidized suspension. The bulk mobility itself also represents a key parameter for characterising quantitatively the observed fluidization-quality in homogeneously fluidized beds.

Measurements have been made for homogeneous gas-fluidization using particles of small size and/or low density, which display significant regions of homogeneous behaviour and which include zones affected by hysteresis phenomena (S C Tsinontides and R Jackson 1993. The mechanics of gas fluidized beds with an interval of stable fluidization. Journal of Fluid Mechanics 255. 37). The velocities of kinematic and dynamic shocks have been measured (via respectively the bed surface velocity following a gas flux step change, and the 'raining down' interface for a bed packed against a top porous plate). Such measurements have been previously performed for liquid fluidized beds (L G Gibilaro, R Di Felice, I Hossain, P U Foscolo 1989. The experimental determination of one-dimensional wave velocities in liquid fluidized beds. Chemical Engineering Science 44. 101) but not for gas ones. Initial results from this research suggest that, in the absence of hysteresis effects, the kinematic and dynamic wave velocities conform well to fluid dynamic model predictions and, together with particle mobility and the apparent bed viscosity, provide a comprehensive basis for the characterisation of homogeneous gas-fluidization quality.

An example of a kinematic wave measurement is shown in Figure 1. The procedure was exactly that referred to above for liquid fluidized beds. Shocks of various magnitude, brought about by a sudden change in fluid flux, were imposed on the fluidized beds and the resulting bed surface velocities measured with the aid of a video record; from these measurements the corresponding kinetic shock velocities are readily obtainable, and may be extrapolated to yield the zero magnitude shock - the kinetic wave - velocity as shown. Linear regression of the calculated shock velocities yields in this case a experimental kinematic wave velocity of 2.05 cm/s, which compares well with the predicted value of 2.02 cm/s.

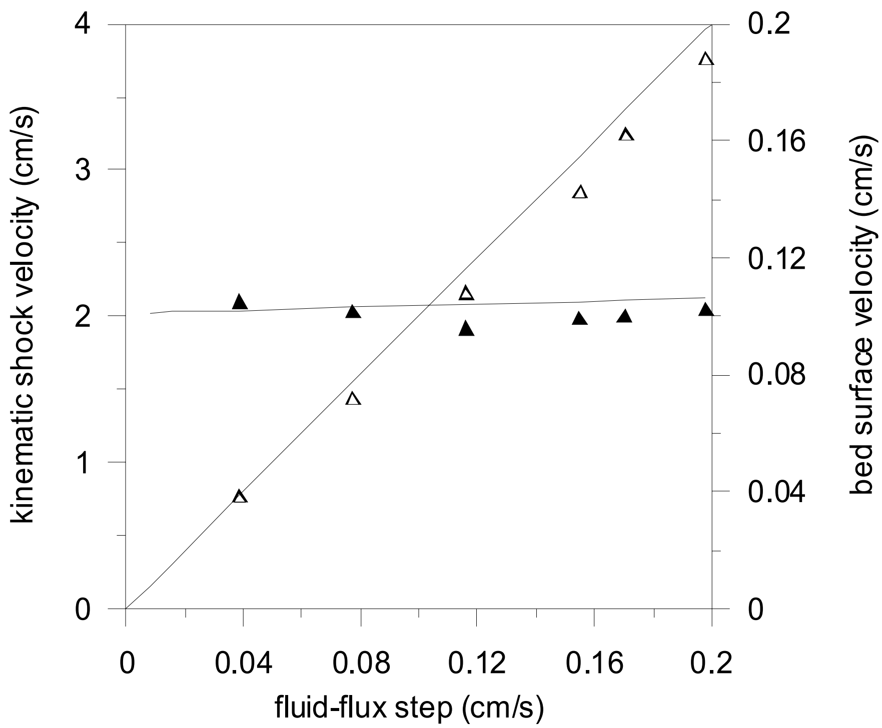

Figure 1. Example of kinematic wave and shock velocities in a gas fluidized bed. System: Ambient air fluidized alumina particles of mean diameter 75 microns and density 873 kg / m^3. The open points represent the measured bed surface velocities (right hand ordinate); from these the kinematic shock velocities (solid points, left hand ordinate) are calculated; the continuous lines represent predicted values

An example of a dynamic wave measurement is shown in Figure 2. Again, the procedure corresponds to that described in the quoted reference for one-dimensional wave velocities in liquid fluidized beds, as first proposed by Wallis (1962. One-dimensional waves in two-component flow with particular reference to the stability of fluidized beds. United Kingdom Atomic Energy Authority Report: AEEW-R162). This also involves an extrapolation of shock velocities, this time in a fixed bed of particles, maintained compacted against a porous plate at the top of a fluidized bed column by a high velocity air flux: on reducing this flux, to a value between that for minimum fluidization and approximately twice that value, the bottom of the packed particle bed 'rains down', resulting in an upwards travelling shock, which at the extrapolated limit, corresponding to the minimum fluidization flux, represents the dynamic wave velocity under minimum fluidization conditions. Figure 2 illustrates this procedure. The experimentally determined dynamic wave velocity corresponds to the extrapolated shock velocity at the minimum fluidization velocity: 8.63 cm/s, which compares with the predicted value of 9.90 cm/s.

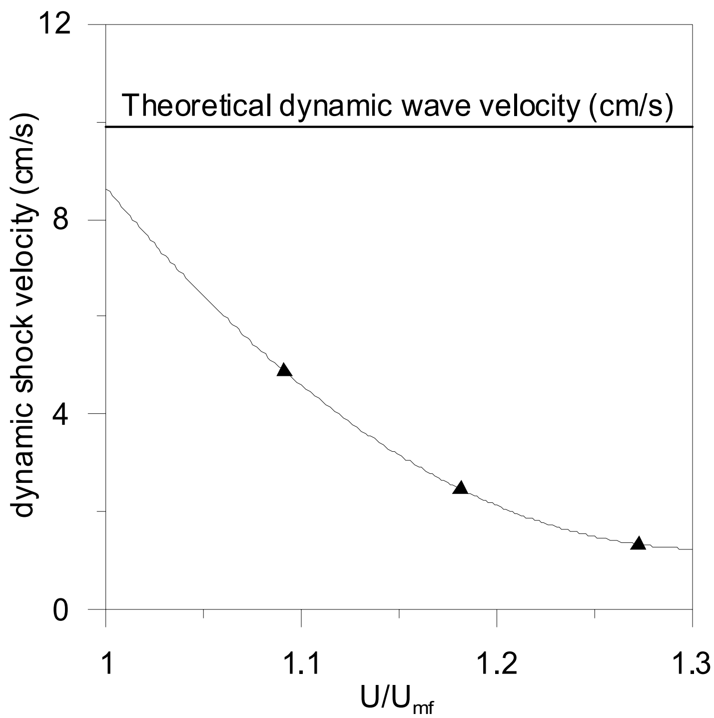

Figure 2. Example of a dynamic wave velocity measurement in a gas fluidized bed by the raining down technique.
System: Ambient air fluidized laposorb particles of mean diameter 520 microns and density 1216 kg / m^3; minimum fluidization gas flux 0.17 m/s.

Fluidized beds display a property analogous to fluid viscosity, which influences the velocity with which objects submerged in the bed either fall or rise. Although empirical studies of this phenomenon have been reported, and the measured fall and rise velocities used to determine values of apparent viscosity for the particular experimental conditions employed, no means have yet been proposed for estimating this important property of a fluidized suspension as a function of the basic system parameters. However, it can be shown that the fluid-dynamic analogy of a typical particle in a fluidized bed inventory as the same particle suspended under terminal conditions in a pseudo-fluid (composed of the fluid and all the other suspended particles) leads to predictive estimates for the apparent viscosity of fluidized beds in good quantitative agreement with reported experimental measurements, for particle concentrations of up to around forty percent. Consider a typical particle of a fluidized bed inventory; the forces to which this particle is subjected may be quantified in terms of the primary equilibrium forces for a fluidized suspension, for which various formulations are readily available: for the predictions shown below, the previously referenced Particle Bed Model has been used for this purpose. Alternatively, the same typical particle may be considered to be suspended alone, under terminal conditions, in a pseudo-fluid (of known apparent density and, as yet, unknown apparent viscosity) consisting of the fluid itself and all the remaining particles. By equating these alternative views, through the bulk mobility parameter proposed by Batchelor, a value for apparent viscosity may be deduced.

Under low Reynolds number conditions, the above procedure yields the following fully predictive expression for apparent suspension viscosity μ_{app}:

$$\mu_{app} = \mu_f \, \varepsilon^{-2.8},$$

where μ_f is the fluid viscosity and ε is the void fraction. Figure 3 compares the predictions of this expression with experimental results presented in the literature by various authors. The broken and continuous curves show the model predictions for water and air fluidization respectively; the solid and open points the reported measurements for air and water fluidization respectively.

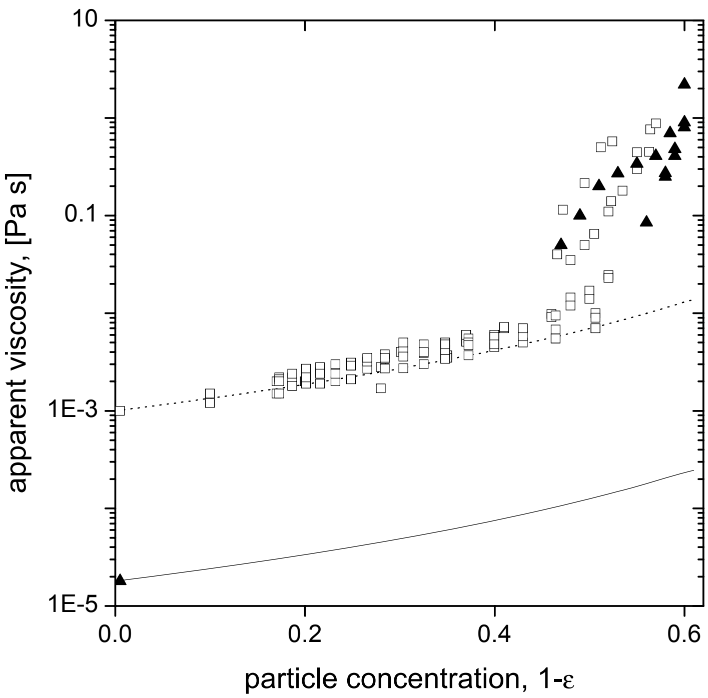

Figure 3. Apparent viscosities of water- and gas-fluidized beds. Comparison of experimental results for spherical particles (points) with model predictions. Gas-fluidization results (solid triangles): reported by Grace (1970. The viscosity of fluidized beds. The Canadian Journal of Chemical Engineering 48. 30-33); reported by King et al. (1981. Dense phase viscosities of fluidized beds at elevated pressures. Powder Technology 28. 55-58.); reported by Rees et al. (2005. The rise of a buoyant sphere in a gas-fluidized bed. Chemical Engineering Science 60. 1143-1153.); reported by Reiling (1992. Effect of type C particles on cohesion and viscosity of Type A powders. In Fluidization VII, Potter, O.E. and Nicklin, D.J., Editors, Engineering Foundation, New York).

Water-fluidization results (open squares): reported by Martin et al. (1981. The falling velocity of a sphere in a swarm of different spheres. Transactions of the Institution of Chemical Engineers 59. 100-104) and van der Wielen et al. (1996. On the relative motion of a particle in a swarm of different particles. Chemical Engineering Science 51. 995-1008); reported by Tsuchiya et al. (1997. Suspension viscosity and bubble rise velocity in liquid-solid fluidized beds. Chemical Engineering Science 52. 3053-3066); reported by Tsuchiya and Furumoto (1995. Tortuosity of bubble rise path in a liquid-solid fluidized bed: effect of particle shape. AIChE Journal 41. 1368-1374).

The primary force formulations of the Particle Bed Model for fluidization have thus been shown to lead to fully predictive estimates for the intrinsic apparent viscosity of a fluidized suspension for particle concentrations of up to about forty percent. Beyond this value, the predictions fall progressively below measured values, almost certainly due to the growing dominance of particle-particle interaction phenomena, brought about by the experimental test conditions adopted. At particle concentrations close to the minimum fluidization condition, this dominance is evidenced by the fact that the measurements cease to be influenced by the properties of the suspending fluid, both liquid- and gas-fluidization giving rise to very similar values for the measured apparent viscosity as this limit is approached. Work is at present underway to measure apparent viscosities of expanded homogeneous air fluidized beds,using a modified Couette device, thereby complementing the above reported results for liquid fluidization at relatively low particle concentration.

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