Inhomogeneity Instability in Vertical Flows

In vertical flows, the inhomogeneity instability described in the last section will mean the development of intermittency in the volume fraction. The short term result of this instability is the appearance of vertically propagating, horizontally oriented kinematic waves (see sections (Ns)) in otherwise nominally steady flows. They have been most extensively researched in fluidized beds but have also be observed experimentally in vertical bubbly flows by Bernier (1982), Boure and Mercadier (1982), Kytomaa and Brennen (1990) (who also examined solid/liquid mixtures at large Reynolds numbers) and analyzed by Biesheuvel and Gorissen (1990). (Some further comment on these bubbly flow measurements is contained in section (Nsd).)

As they grow in amplitude these wave-like volume fraction perturbations seem to evolve in several ways depending on the type of flow and the manner in which it is initiated. In turbulent gas/liquid flows they result in large gas volumes or slugs with a size close to the diameter of the pipe. In some solid/liquid flows they produce a series of periodic vortices, again with a dimension comparable with that of the pipe diameter. But the long term consequences of the inhomogeneity instability have been most carefully studied in the context of fluidized beds. Following the work of Jackson (1963), El-Kaissy and Homsy (1976) studied the evolution of the kinematic waves experimentally and observed how they eventually lead, in fluidized beds, to three-dimensional structures known as *bubbles* . These are *not* gas bubbles but three-dimensional, bubble-like zones of low particle concentration that propagate upward through the bed while their structure changes relatively slowly. They are particularly evident in wide fluidized beds where the lateral dimension is much larger than the typical interparticle distance. Sometimes bubbles are directly produced by the sparger or injector that creates the multiphase flow. This tends to be the case in gas-fluidized beds where, as illustrated in the preceding section, the rate of growth of the inhomogeneity is much greater than in liquid fluidized beds and thus bubbles are instantly formed.

Because of their ubiquity in industrial processes, the details of the three-dimensional flows associated with fluidized-bed bubbles have been extensively studied both experimentally (see, for example, Davidson

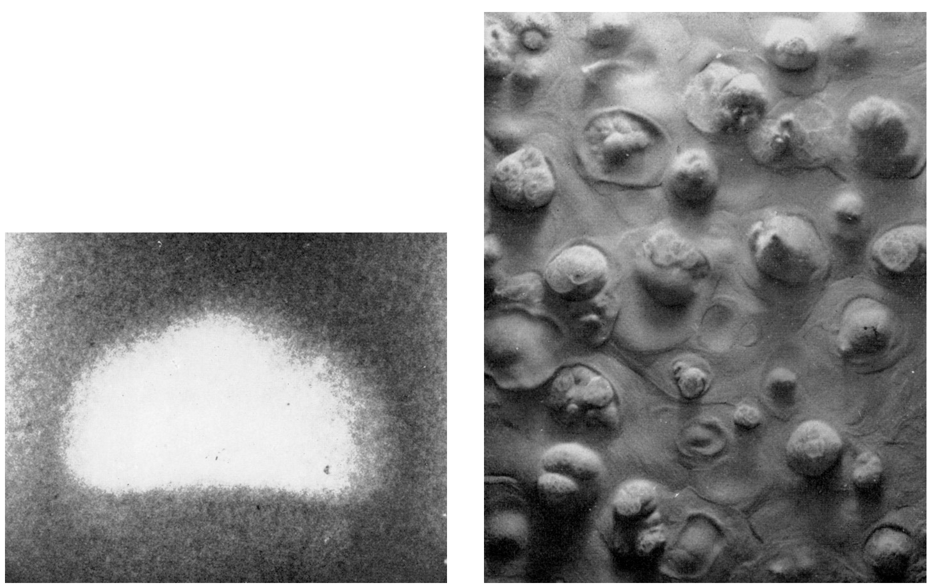

Figure 1: Left: X-ray image of fluidized bed bubble (about $5cm$ in diameter) in a bed of glass beads (courtesy of P.T.Rowe). Right: View from above of bubbles breaking the surface of a sand/air fluidized bed (courtesy of J.F.Davidson).

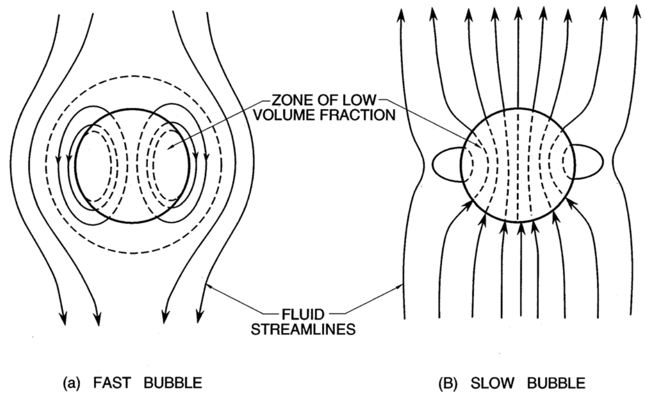

Figure 2: Sketches of the fluid streamlines relative to a fluidized bed *bubble* of low volume fraction for a *fast* bubble (left) and a *slow* bubble. Adapted from Catipovic *et al.* (1978).

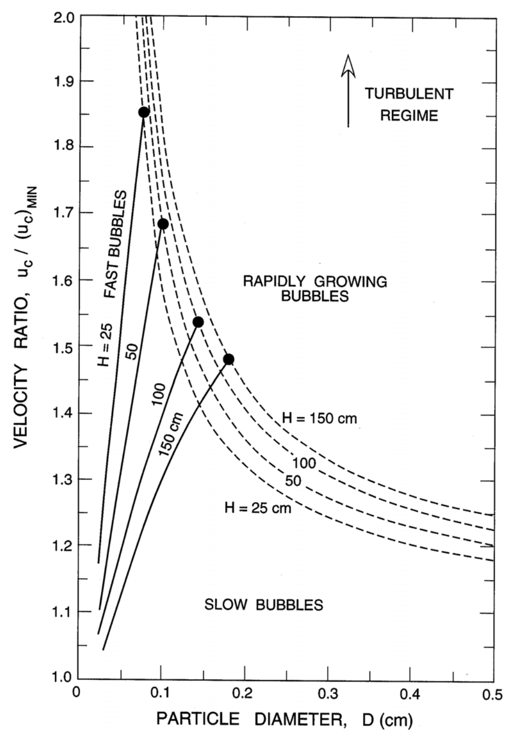

Figure 3: Flow regime map for fluidized beds with large particles (diameter, D) where $(u_C)_{min}$ is the minimum fluidization velocity and H is the height of the bed. Adapted from Catipovic *et al.* (1978).

and Harrison 1963, Davidson *et al.* 1985) and analytically (Jackson 1963, Homsy *et al.* 1980). Roughly spherical or spherical cap in shape, these zones of low solids volume fraction always rise in a fluidized bed (see figure 1). When the density of bubbles is low, single bubbles are observed to rise with a velocity, W_B, given empirically by Davidson and Harrison (1963) as

$$W_B = 0.71 g^{\frac{1}{2}} V_B^{\frac{1}{6}} \tag{Njn1}$$

where V_B is the volume of the bubble. Both the shape and rise velocity have many similarities to the spherical cap bubbles discussed in section (Nfc). The rise velocity, W_B may be either faster or slower than the upward velocity of the suspending fluid, u_C, and this implies two types of bubbles that Catipovic *et al.* (1978) call *fast* and *slow* bubbles respectively. Figure 2 qualitatively depicts the nature of the streamlines

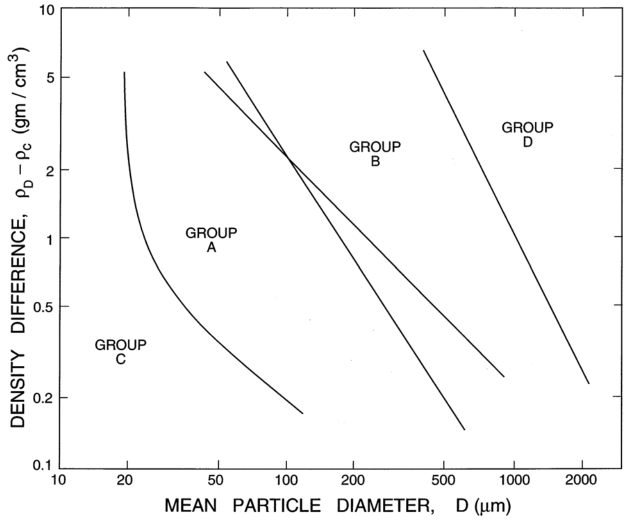

Figure 4: Flow regime map for fluidized beds with small particles (diameter, D). Adapted from Geldart (1973).

of the flow relative to the bubbles for fast and slow bubbles. The same paper provides a flow regime map, figure 3 indicating the domains of fast bubbles, slow bubbles and rapidly growing bubbles. When the particles are smaller other forces become important, particularly those that cause particles to stick together. In gas fluidized beds the flow regime map of Geldart (1973), reproduced as figure 4, is widely used to determine the flow regime. With very small particles (Group C) the cohesive effects dominate and the bed behaves like a plug, though the suspending fluid may create holes in the plug. With somewhat larger particles (Group A), the bed exhibits considerable expansion before bubbling begins. Group B particles exhibit bubbles as soon as fluidization begins (fast bubbles) and, with even larger particles (Group D), the bubbles become slow bubbles.

Aspects of the flow regime maps in figures 3 and 4 qualitatively reflect the results of the instability analysis of the last section. Larger particles and larger fluid velocities imply larger j_{CD} values and therefore, according to instability analysis, larger growth rates. Thus, in the upper right side of both figures we find rapidly growing bubbles. Moreover, in the instability analysis it transpires that the ratio of the wave speed, ω/κ (analogous to the bubble velocity) to the typical fluid velocity, j_{CD}, is a continuously decreasing function of the parameter, $j_{CD}/(g/\kappa)^{\frac{1}{2}}$. Indeed, $\omega/j_{CD}\kappa$ decreases from values greater than unity to values less than unity as $j_{CD}/(g/\kappa)^{\frac{1}{2}}$ increases. This is entirely consistent with the progression from fast bubbles for small particles (small j_{CD}) to slow bubbles for larger particles.

For further details on bubbles in fluidized beds the reader is referred to the extensive literature including the books of Zenz and Othmer (1960), Cheremisinoff and Cheremisinoff (1984), Davidson *et al.* (1985) and Gibilaro (2001).