PSRI Lectureship in Fluidization Award 2016

The Dynamics of Normal, Inverse and Sheared Fluidized Beds

Benjamin J. Glasser, Department of Chemical and Biochemical Engineering

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

Introduction

Fluidized beds occur extensively in the chemical, petrochemical and pharmaceutical industry. Most fluidized beds are unstable to low amplitude disturbances and develop non-uniform particle distributions in the form of density waves. In fluidized beds such non-uniformities can become amplified in the bed to form fully developed bubbles (in dense fluidized beds) [1], clusters and streamers (in dilute fluidized beds) [2, 3] and slugs (in narrow fluidized beds) [1]. Since the presence of voidage or density waves are known to dramatically impact heat and mass transfer rates, and process safety and economics, it is important to understand the underlying physical mechanisms responsible for unstable flow behavior. At the same time, the dynamics of dense gas-particle suspensions are heavily influenced by granular rheology, and granular flows, by themselves can undergo instabilities. Thus, instabilities manifested by granular flows are observed in fluidized beds and an understanding of granular behavior and stresses is needed for fluidization models.

Using continuum mechanics, volume- or ensemble-averaged equations of mass and motion have been postulated to describe the flow of the fluid and particle phases in fluidized beds [4]. It is common to derive the constitutive relations for the solid phase momentum equation from the kinetic theory of dense gases [5-8]. The main difference between molecular gases and granular particles is that energy is lost due to collisions between particles, while this is not true for molecular gas collisions.

For unbounded gas-particle flows, the simplest solution to the governing equations of motion represents the steady state of uniform fluidization. In order to predict the growth of disturbances from the steady base-state, conventional methods of hydrodynamic stability analysis have been applied [9-15]. The earliest stability analysis from the work of Jackson [13] predicted that uniform fluidized beds are inherently unstable, and that such instabilities are in the form of plane waves, which propagate vertically upwards through the bed. Although linear theory can account for the existence of traveling waves in gas-fluidized beds, it can only capture phenomena occurring in close proximity to the marginal stability point. Therefore, it is not capable of predicting the ultimate fate of the instability. In order to better understand the origin of bubbles, the nonlinear terms in the equations of motion have been taken into account in one-dimensional fluidized beds [16-19]. Results of non-linear analyses have shown that low amplitude disturbances can become amplified in fluidized beds to form fully-developed one-dimensional traveling waves [19].

From Bubbles to Clusters in Fluidized Beds

Bifurcation theory has been used to investigate the behavior of traveling waveforms in unbounded fluidized beds [20-24]. Using bifurcation analysis and a numerical continuation approach [20, 23] it was demonstrated that one–dimensional (1D) traveling wave solutions bifurcating from the uniform base state are unstable in the transverse direction, and that this can lead to the formation of bubble-like structures. In Figure 1, some typical bubble-like structures are shown for a gas-fluidized bed. These represent traveling waves that move up through the fluidized bed at a constant velocity. Contour plots of solids fraction along with streamlines of the gas velocity are shown in the figure. It is important to check the robustness of the bifurcation behavior by considering different gas-particle systems. This is particularly important as bubbles are formed easily in gas-fluidized beds and therefore the ability to observe them in mathematical models should not be restricted to a specific set of closures or parameters. A long series of numerical experiments were carried out by changing the model parameters and the closures and it was found that the bifurcation behavior was robust in the following sense: the traveling waves having only vertical structure emerge through a Hopf bifurcation of an unstable uniform state and the 2D traveling waves are born out of these 1D traveling waves. The high amplitude 2D traveling waves resemble bubbles in fluidized beds.

It was later established that bubbles and clusters belong to the same family of non-uniform traveling wave solutions [24]. Using a bifurcation analysis the solution structure of volume-averaged equations of motion describing unbounded fluidized beds was examined, and it was found that by varying parameters of the system, it was possible to move smoothly between the seemingly different structures observed in fluidized beds, namely bubbles and clusters. In Figure 2, contour plots of solids fraction are shown for traveling waves in gas-fluidized beds for both bubble-like and cluster-like solutions. It was observed that the traveling waves propagate in the following way: when the lower surface of a dense region becomes unstable, particles (within the solids rich region) "rain" down to fill the dilute region below. Once they pass through the dilute region, they enter the upper surface of another solids rich region. Hence, for any particle dense region, particles are lost from its lower surface and simultaneously collected on its upper surface. It is this mechanism that leads to the propagation of the density wave.

Additional work investigated instabilities in inverse fluidized beds (where the particle density is less than fluid density) and the hierarchy of bifurcations was compared to normal fluidized beds. It was shown that the Froude number and fluid to solid density ratio control the behavior of instabilities [25]. The physical mechanisms leading to density inhomogeneities in gas-fluidized beds were further investigated and it was shown that under certain simplifying assumptions, model equations of motion and continuity for the particles in a fluidized bed, can be related to those of a compressible fluid acted upon by a density dependent force. A comparison of these results with previous work on gas-fluidized beds showed that the salient features of the instability of a gas-fluidized bed are captured by the basic physics of compressible flows.

Instabilities in Bounded Fluidized Beds

Previous work had established that steady flows of gas and particles in unbounded fluidized beds lose stability to localized voidage disturbances. Work was carried out to investigate the stability of bounded gas-particle flows. The stability analysis was carried out for two sets of boundary conditions corresponding to fluidized systems having walls acting as sinks and sources of fluctuation energy [26]. The linear stability of the base state was examined by imposing a perturbation on the steady state solution in the form of a localized periodic disturbance. The governing equations and boundary conditions were then expanded in ascending powers of the perturbations through a Taylor series expansion of the nonlinear terms. Since the disturbances were assumed to be both small and smoothly varying in space and time, their derivatives were also small. Therefore, all terms of degree greater than one in the perturbations were neglected. Perturbations were assumed to take the form of a plane wave disturbance. Instabilities were characterized by computing leading eigenvalue profiles and dominant eigenfunction contour maps. The results showed two types of dominant instability patterns (symmetric and anti-symmetric) for flow in a vertical duct, both of which propagate through the bed in the form of traveling waves at speeds comparable to that of the solid phase. Moreover, model predictions showed that increasing solids fraction and decreasing particle inelasticity suppresses the disturbances. The physical mechanism of instability formation was further investigated using a term-by-term method of analysis. Results showed that the instability modes can be suppressed if solid phase inertia or inelastic particle collisions are eliminated from the momentum and pseudo-thermal energy balance equations. Moreover, it was shown that the occurrence of symmetric instability patterns is due to the inclusion of gas-phase inertia. Finally, the symmetric instabilities were shown to develop into bubble-like structures while the anti-symmetric instabilities develop into streamer-like structures. In Figure 3, a stability map is presented as a function of the average solids fraction, ϕ, and the coefficient of restitution of the particles, ep. Within the physical parameter space, a stability analysis shows the dominant mode in the ϕ-ep plane has three types of structures: stable patterns; symmetric unstable patterns; and anti-symmetric unstable patterns. Contour plots of solids fraction are also shown in Figure 3 to showcase a symmetric and anti-symmetric instability. These contour plots were obtained by adding a small perturbation to the steady state solution. The symmetric instability leads to cluster-like or bubble-like solutions, while the anti-symmetric instability leads to a streamer-like solution [26].

Binary mixtures of particles in fluidized beds were computationally investigated for unbounded and bounded flows. In bounded flows it was observed that segregation could occur due to competition of three diffusion forces: the thermal diffusion force, the ordinary diffusion force, and the pressure diffusion force [27]. A number of different binary mixtures were examined: 1) equal density particles with different sizes, 2) equal mass particles with different sizes and 3) equal size particles with different masses. It was observed that the species segregation in the solid phase is enhanced with a decrease in the system inelasticity, an increase in the average solids fraction or an increase in the size ratio, due to the competition of the three diffusion forces. In addition, it was found that a competition mechanism exists in the equal density case (particles with equal density but different sizes) since in the equal mass case (particles with equal mass but different sizes) small particles have a higher concentration in low granular energy regions whereas in the equal size case (particles with equal size but different masses) heavy particles have a higher concentration in low granular energy regions. By investigating equal size and equal mass systems, it was found that the breakdown of energy equipartition is mainly due to the contribution of the mass disparity, whereas the effect of the size disparity is very small if the two particle species have the same mass. For equal size particles, the flow profiles exhibit a transition with the variation of the mass ratio. For small mass ratios, the segregation between two particle species increases with an increase in the mass ratio. However, further increasing the mass ratio reverses the situation. Similar transitions were observed when the variation of the diffusion force profiles was tracked with the mass ratio. These findings are in agreement with the results for granular Couette flows. The flow of binary mixtures of particles in a fluidized bed was compared to flow of binary mixtures of particles in a channel without a gas i.e. granular channel flow. It was found that the species segregation profiles are quite similar between the bidisperse granular flows and the bidisperse gas-particle flows.

Instabilities in Sheared Fluidized Beds

A sheared fluidized bed was investigated by rotating an inner cylinder in a cylindrical fluidized bed, generating a Taylor-Couette flow. Inherent periodicity in the Taylor-Couette flow allows large length and timescales to be accessed, and so the fluidized Couette device represents a bench-top apparatus which allows for granular instabilities to form and their effect on segregation to be studied. It was observed that vortices developed and the observed instability was consistent with the Taylor-Couette instability in fluids [28]. As can be seen in Figure 4, a variety of horizontal banded structures spontaneously form in the fluidized Couette flows of binary granular materials. Shear was carried out in a well-mixed, fluidized binary mixture consisting of equal parts 138μm (white) and 462μm (rust) spheres. Particle motion (observed at the free surface) is at first azimuthal and confined to a narrow zone near the moving wall. This zone widens with rising rotation rate until it reaches the outer wall. Once particles start moving at the outer wall, a transition is seen in which particles begin to flow radially outward at the upper surface and downward along the outer wall. Particle segregation by size is observed both on the upper surface as a ring of the larger particles surrounding the inner cylinder, and as subsurface axial segregation (visible through the outer wall). These bands appear spontaneously from a well-mixed state after one to two minutes. Once formed, they are stable for all times we have considered (up to ten minutes). Upon increasing the rotation rate, the bands appear to sometimes split into two daughter bands, which may be alternately “thick” and “thin”. A variety of initial conditions (well-mixed, vertically segregated, horizontally segregated) all yield the same segregated state.

Concluding Remarks

While we have an understanding of many aspects of instabilities in fluidized beds, a large number of research questions remain unanswered. One would like a better understanding of scale up in fluidized beds. Ideally one would like to carry out experiments and simulations for a bench scale apparatus and use the results to predict behavior at the pilot scale and manufacturing scale. One would like to be able to do this with heat transfer, mass transfer and reactions in order to predict the scale up of chemical reactors. Another important area of research is further development of closures for two phase flow equations; in particular, further work is needed for the solids phase stress for non-spherical and cohesive particles. In addition, more work on coarse graining for CFD and CFD-DEM of gas particle flows is needed in order to resolve manufacturing scale fluidized beds.

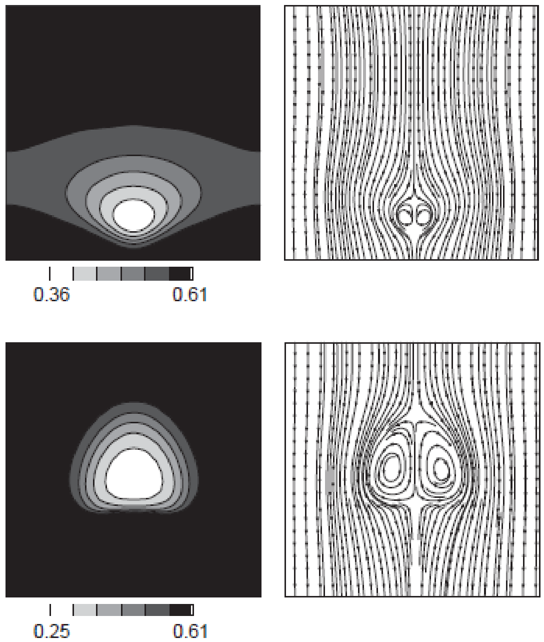

Figure 1: Contour plots of solids fraction (left) and streamlines of gas velocity (right) for a low amplitude traveling wave (top panels) and a high amplitude traveling wave (bottom panels). The high amplitude traveling wave has the essential features of a bubble in a gas-fluidized bed [20].

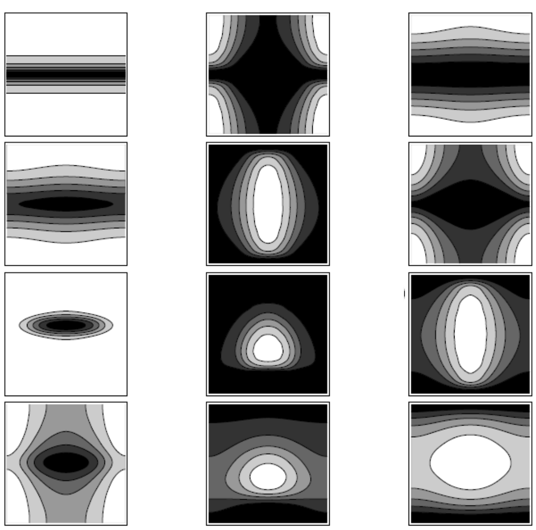

Figure 2: Contour plots of solids fraction. Plots are traveling wave solutions for volume averaged equations of motion for gas-fluidized beds [24]. The results show that bubble-like and cluster-like solutions belong to the same family of non-uniform solutions.

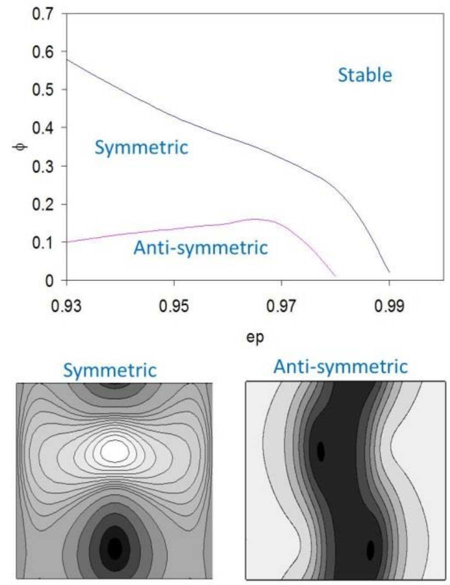

Figure 3: Instabilities in a bounded fluidized bed. Top: stability map as a function of the average solids fraction, ϕ, and the coefficient of restitution, ep, of the particles. Bottom: contour plots of solids fraction for a symmetric (left) and anti-symmetric instability (right). The contour plots were obtained by adding a small perturbation to the steady state solution [26].

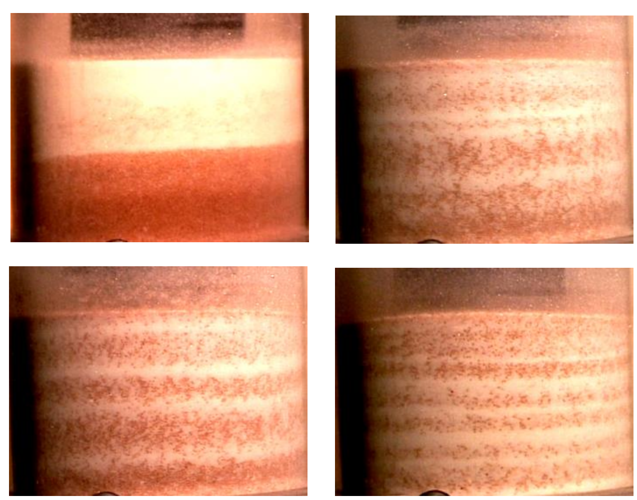

Figure 4: Segregation in a Taylor-Couette fluidized granular bed. Banding patterns for fluidized granular flows for white (138 μm) and rust (462 μm) particles, 50/50 vol% mixture. The fluidized granular bed is imaged through a transparent outer cylinder. The number of bands increases as the rotation rate increases [28].

References

1. Kunii, D. and O. Levenspiel, *Fluidization Engineering*. 1991: Butterworth-Heinemann.
2. Juan, A.H., *Instabilities induced by concentration gradients in dusty gases.* J. Fluid Mech., 2001. **435**: p. 247-260.
3. Agrawal, K., et al., *The role of meso-scale structures in rapid gas–solid flows.* J. Fluid Mech., 2001. **445**: p. 151-185.
4. Jackson, R., *The Dynamics of Fluidized Particles*. 2000: Cambridge University Press.
5. Lun, C.K.K., et al., *Kinetic theories for granular flow: inelastic particles in couette flow and slightly inelastic particles in a general flow field.* J. Fluid Mech., 1984. **140**(223-256).
6. Lun, C.K.K., *Kinetic theory for granular flow of dense, slightly inelastic, slightly rough spheres.* J. Fluid Mech., 1991. **233**: p. 539-559.
7. Jenkins, J.T. and S.B. Savage, *A theory for the rapid flow of identical, smooth, nearly elastic, spherical particles.* J. Fluid Mech., 1983. **130**: p. 187-202.
8. Jenkins, J.T. and M. Richman, *Kinetic theory for plane flows of a dense gas of identical, rough, inelastic, circular disks.* Phys. Fluids, 1985. **28**: p. 3485-3494.
9. Anderson, T.B. and R. Jackson, *A fluid mechanical description of fluidized beds. Equations of motion.* Ind. Eng. Chem. Fundam., 1967. **6**: p. 527-539.
10. Anderson, T.B. and R. Jackson, *Fluid mechanical description of fluidized beds. Stability of the state of uniform fluidization.* Ind. Eng. Chem. Fundam., 1968. **7**: p. 12-21.
11. Pigford, R.L. and T. Baron, *Hydrodynamic stability of a fluidized bed.* Ind. Eng. Chem. Fundam., 1965. **4**: p. 81-87.
12. Bachelor, G.K. and J.M. Nitsche, *Instability of stationary unbounded stratified fluid.* J. Fluid Mech., 1991. **227**: p. 357-391.
13. Jackson, R., *the mechanics of fluidized beds. I: the stability of the state of uniform fluidization.* Trans. Inst. Chem. Eng., 1963. **41**: p. 13-21.
14. Bachelor, G.K., *Secondary instability of a gas-fluidized bed.* J. Fluid Mech., 1993. **257**: p. 359-371.
15. Koch, D.L.S., A. S., *Particle pressure and marginal stability limits for a homogeneous monodisperse gas fluidized bed: kinetic theory and mumerical simulation.* J. Fluid Mech., 1999. **400**: p. 229-263.
16. Fanucci, J.B., N. Ness, and R.H. Yen, *On the formation of bubbles in gas-particle fluidized beds.* J. Fluid Mech., 1979. **94**: p. 353-367.
17. Hirayama, O. and R. Takaki, *Analysis of nonlinear waves in a one-dimensional fluidized bed.* Fluid Dyn. Res., 1997. **21**: p. 233-247.
18. Liu, J.T.C., *Nonlinear unstable wave disturbances in fluidized beds.* Proc. R. Soc. Lond. A., 1983. **389**: p. 331.
19. Needham, D.J. and J.H. Merkin, *The propagation of voidage disturbances in a uniform fluidized bed.* J. Fluid Mech., 1983. **131**: p. 427-454.
20. Glasser, B.J., I.G. Kevrekidis, and S. Sundaresan, *One- and two-dimensional travelling wave solutiuons in gas fluidized beds.* J. Fluid Mech., 1996. **306**: p. 183-221.
21. Goz, M.F., *On the origin of wave patterns in fluidized beds.* J. Fluid Mech., 1992. **240**: p. 379-404.
22. Goz, M.F., *Bifurcation of plane voidage waves in fluidized beds.* Physica D, 1993. **65**: p. 319-351.
23. Glasser, B.J., I.G. Kevrekidis, and S. Sundaresan, *Fully developed travelling wave solutions and bubble formation in fluidized beds.* J. Fluid Mech., 1997. **334**: p. 157-188.
24. Glasser, B.J., S. Sundaresan, and I.G. Kevrekidism, *From bubbles to clusters in fluidized beds.* Phys. Rev. Lett., 1998. **81**: p. 1849-1852.
25. Howley, M.A. and B.J. Glasser, *A comparison of one-dimensional traveling waves in inverse and normal fluidized beds.* Physica D: Nonlinear Phenomena, 2005. **201**(1–2): p. 177-198.
26. Liu, X., B.J. Glasser, and M.A. Howley, *Instability of bounded gas-particle fluidized beds.* AIChE Journal, 2007. **53**(4): p. 811-824.
27. Liu, X., M. Metzger, and B.J. Glasser, *Granular and gas–particle flows in a channel with a bidisperse particle mixture.* Chemical Engineering Science, 2008. **63**(23): p. 5696-5713.
28. Conway, S.L., T. Shinbrot, and B.J. Glasser, *A Taylor vortex analogy in granular flows.* Nature, 2004. **431**(7007): p. 433-437.