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BOOK REVIEW

The Dynamics of Fluidized Particles. By R. Jackson, Cambridge University Press, 2000. 339 pp. ISBN 0521781221. £ 42.50

Fluidization is a process whereby a bed of granular material is given the properties of a liquid by an upward flow of fluid through the interstices of the granular bed. Thus when air is blown upwards through a bed of sand, for example, the pressure drop increases progressively with flow, until the weight of the bed is fully supported by the pressure drop across it: at this point the bed is fully fluidized; subsequent increments of air flow pass through as bubbles, causing the bed to take on the appearance of boiling liquid.

This process was used to good effect during World War II for the production of aviation gasoline from involatile components of crude oil. The *catalytic cracker*, based on large fluidized beds, soon became a feature of every large oil refinery. Fluidization has been used over the last fifty years for many other processes, e.g. gas–solid polymerization.

Over this period, much research has been directed towards understanding the science of fluidization, giving many publications describing experiments and theoretical modelling. This book by Roy Jackson is a most welcome addition to this literature, for he has, perhaps more than anyone else, been responsible for developing fundamental theories that give a proper representation of behaviour, comparable to that available for single-phase fluids in the form of the Navier–Stokes equations.

As he describes, concisely on pp. 2–3, three methods of formulating equations of motion have been developed and I quote:

> 1. At the most fundamental level the motion of the whole system is determined by the Newtonian equations of motion for the translation and rotation of each particle and the Navier–Stokes and continuity equations, to be satisfied at every point of the interstitial fluid. These are linked by the no-slip condition between the solid and the fluid on each particle boundary, and the fluid must also satisfy no-slip conditions everywhere on the walls bounding the entire system of interest. Calculations at this level of detail have been performed successfully, but only for quite small numbers of particles.
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> 2. A second description, at a less detailed level, can be obtained by replacing the fluid velocity at each point by its average, taken over a spatial domain large enough to contain many particles but still small compared to the whole region occupied by the flowing mixture. The force exerted by the fluid on each particle is then related to the particle's velocity relative to this *locally averaged* fluid velocity, and to the local concentration of the particle assembly, using one of a number of empirical correlations. The Newtonian equations of motion are then solved for each particle separately, taking into account direct collisions between particles when this is appropriate. This procedure, sometimes referred to as 'discrete particle modelling', is much less demanding computationally than a complete solution at the first level of detail.
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> 3. At a third level of detail both the fluid velocity and the particle velocity are averaged over the local spatial domains introduced above. There are then two local-averaged velocity fields, $\mathbf{u}$ and $\mathbf{v}$, for the fluid and the particles respectively. Each of these is defined at all points of space, so that the resulting equations *look like* the equations of motion one would write for two imaginary fluids, capable of interpenetrating so that every point is occupied simultaneously by both fluids. Consequently, a description at this level of detail if often referred to as a 'two fluid model'.

Methods (1) and (2) are, on the face of it, the most fundamentally based because they follow the motion of every particle. But these methods are not without empirical factors such as coefficients of restitution between colliding particles and wall friction coefficients. Moreover, methods (1) and (2) impose severe demands on computer memory. Thus method (2) has been successful for predicting the behaviour of a laboratory bed containing large particles: for example in a 0.2 m cube containing 1 mm particles, the computer has to follow the fortunes of about 10^7 particles. But an industrial unit might be represented by a 10 m cube containing 100 µm particles of which there would be about 10^{15}; perhaps the time is not too far off when computers will be able to follow 10^{15} particles, who can tell?

In the meantime, the author was no doubt wise to concentrate his research, and the theme of the book, on model 3, the 'two-fluid model' which has been used successfully by a number of workers, giving good qualitative descriptions of fluidized bed behaviour, e.g. bubble shape and coalescence. The two-fluid model is the subject of some uncertainty in that a variety of equations have been published, with significant differences in important terms. Anyone wishing to use the two-fluid model is faced with a free-market economy offering a variety of options. Here Jackson's book is helpful: it gives a critique of published models in Chapter 2. The discussion includes an attractively simple test, aptly described as an 'analogue of Galileo's famous 'Pisa' experiment': a uniform dispersion of particles in a body of fluid, all released from rest, ought to fall with the common acceleration due to the gravitational field. It is striking that some of the published two-fluid model equations do not pass this simple test. The chapter also contains a useful discussion of assumptions needed for closure of the two-fluid model equations, notably the drag between particles and fluidizing fluid, necessarily an empirical relation. There is also the question of interaction between particles due to inter-particle collisions: a common assumption is to assign a value to the fluidized bed viscosity, typically several hundred times that of water. Readers may wish for a more detailed discussion of this important quantity and its effect on the character of solutions of the two-fluid model, but see below.

Applications of the two-fluid model are discussed in Chapters 4 and 5. Chapter 4 deals with stability analysis and Chapter 5 with bubbles. Jackson's pioneering work on stability analysis is reported in Chapter 4 and there is an admirable comparison with later work. The two-fluid model is shown to predict that fluidized particles are unstable but that gas-fluidized beds are much more unstable than liquid-fluidized beds. There is a refreshing comparison between theory and experiment (Table 4.3) which brings to mind a comment by Jackson that people are now classified as theoreticians or experimentalists, but he simply wants to understand what's going on: the work in Chapter 4 indicates that he is both a competent experimentalist and a first rate theoretician, surely the recipe for good science.

Chapter 5 summarizes the extensive work that has been done over the last forty years on the motion of gas bubbles in gas-fluidized beds and the question of the origin of such bubbles, i.e. their genesis from stability analysis using the two-fluid model. Computational fluid dynamics (CFD) using the two-fluid model has shown how instability in a water-fluidized bed leads to what are nearly bubbles (pp. 187 and 213) using an effective fluid bed viscosity of 6–7 poise. By contrast, CFD gives a prediction of gas bubble development in good agreement with experiment (pp. 228–229) with a 'particle phase pressure dependent on particle concentration, but no viscous terms …'. This leaves the reader with the impression that the fluid bed viscosity is an equivocal component of the two-fluid model.

Chapter 3 is independent of the other chapters. It summarizes Jackson's work on the processes of fluidization and defluidization, much the best published work on what happens near and around incipient fluidization. Concepts of soil mechanics, for describing the relation between interparticle stress and solids volume fraction, are used to explain familiar relations between observed bed pressure drop and flow velocity, particularly the well-known hysteresis between rising and falling flow velocity. Chapter 3 concludes with a fascinating, but all too brief, discussion of the work of Cody & Goldfarb (1996) who measured noise due to particle motion: they found that noise, i.e. particle motion, is negligible until the flow velocity is 4.57 times the velocity for incipient fluidization, consistent with the existence of yield stresses much above incipient fluidization. One wishes here for more discussion, e.g. what is the link between Cody & Goldfarb's result and the well-known fact that fine particles, with a very uniform distributor, exhibit bubble-free behaviour for gas velocities much above incipient fluidization?

Chapter 3 is linked with Chapter 7, which deals with the recondite but industrially important problem of standpipe flow. In the standpipe, particles flow down a vertical pipe, perhaps 1 m diameter, with flow regimes that vary throughout the (large) height of the pipe: there may be bubbling flow in one part and partly fluidized flow in other parts of the pipe. Chapter 7 is a useful summary of Jackson's own work on this difficult problem.

Chapter 6 deals with the even more difficult problem of riser flow: particles and gas are fed into the bottom of a vertical duct, square or circular, which may be huge; $5\,\mathrm{m} \times 5\,\mathrm{m}$ ducts are commonplace. The gas carries the particles up in turbulent flow, with much downflow of particles near the walls and particles concentrated in streamers or clusters. Chapter 6 describes theoretical models, e.g. for 'pseudo turbulent flow', which are related to the basic equations described in Chapter 2. Chapter 6 reports some success in the prediction of velocity profiles, solids fluxes and solids volume fractions. It is impressive that some of the models predict that near the walls there is high solids volume fraction, and solids downflux: many experimenters have reported such downflow of dense particulate phase.

The above gives highlights from an excellent book. The book is intended for readers of *Journal of Fluid Mechanics*. While the discussion is clear and there is at all times a link between the equations and physical reality, the book is not light reading. Engineers are recommended to try hard (this reviewer had to!). The book will be useful to engineers seeking to advance the science of fluidization and also to those with immediate problems: anyone considering the purchase or rental of an expensive CFD package, should ask questions like 'Do the CFD equations pass the tests in the book?' A mild criticism is that, in common with JFM, there is no notation list. The late George Batchelor was adamant in his refusal to include notation lists and this view appears to persist with the present Editors. But notation lists do improve accessibility and help the engineer in a hurry: also, dare one say it, the compilation of a notation list adds discipline and even rigour.

REFERENCE

Cody, G. D. & Goldfarb, D. J. 1996 Discontinuity in particle granular temperature of gas fluidized beds across Geldart A/B boundary. *Materials Research Soc. Fall Meeting, Boston, Dec. 2–6.*

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