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Introduction: the fluidized state

Fluidization

Fluidization is a process whereby a bed of solid particles is transformed into something closely resembling a liquid. This is achieved by pumping a fluid, either a gas or a liquid, upwards through the bed at a rate that is sufficient to exert a force on the particles that exactly counteracts their weight; in this way, instead of a rigid structure held in place by means of gravity-derived contact forces, the bed acquires fluid-like properties, free to flow and deform, with the particles able to move relatively freely with respect to one another.

A number of colourful demonstrations have been devised to illustrate this transformation. One that for many years occupied a prime position in the Chemical Engineering Department laboratories at University College London, later to appear at the Science Museum in Kensington, involved a bed of fine sand and, among other artefacts, two toy ducks, one plastic and one brass. The low-density plastic duck is buried deep in the sand and the high-density brass one is placed on the surface; a compressed air supply to the bottom of the bed is then turned on and the flow progressively increased. When the fluidization point is reached the brass duck sinks to the bottom and the plastic one pops to the surface, where it floats about just as it would in water.

The same principle can be observed in another demonstration, which serves a practical as well as an heuristic purpose. This time, salt crystals are fluidized with air in a container fitted with an electric immersion heater. For reasons that will be discussed in the following chapters, the beds described in both this and the previous example come to resemble a *boiling* liquid at air flow rates above that required to just fluidize the bed; bubbles of air rise rapidly through the fluidized particles causing vigorous mixing, and then burst through the surface – just like steam bubbles in boiling water. This mixing, induced by the bubbles, ensures that the whole bed acquires a uniform temperature. The demonstration now involves dropping corn grains on to the bed surface; their density is a little greater than that of the hot salt suspension, so they sink initially, then heat up and 'pop'. The low-density popcorn immediately rises to the surface, ready salted, for collection and consumption.

This second demonstration illustrates a number of useful features of the fluidized state as a processing environment. In addition to the obvious advantages resulting from the acquisition by the particles of fluid-like properties, which permit them to flow freely from one location to another, the high level of particle mixing means that heat and mass can be rapidly transferred throughout the bed, with far-reaching consequences for its performance as a chemical reactor.

Applications

A major application of fluidized bed technology is to be found in the catalytic-cracking reactor, or 'Cat Cracker', which lies at the heart of the petroleum refining process. Here, the catalyst particles (which promote the breakdown of the large crude petroleum molecules into the smaller constituents of gasoline, diesel, fuel oil, etc.) are fluidized by the vaporized crude oil. An unwanted by-product of the reactions is carbon, which deposits on the particle surfaces, thereby blocking their catalytic action. The properties of the fluidized state are further exploited to overcome this problem. The catalyst is reactivated continuously by circulating it to another bed, where it is fluidized with air in which the carbon burns away, and then back again, regenerated, to continue performing its allotted catalytic function.

Other applications, established and potential, are boundless. Gas-fluidized beds are widely used as chemical reactors, and also as combustors to raise steam for power generation. This latter application can involve the burning of coal, and both urban and agricultural waste, in air-fluidized sand beds. Agricultural waste and purpose-grown energy crops can be fluidized in steam to produce a hydrogen-rich fuel gas. Liquid-fluidized beds are employed extensively in water treatment, minerals processing and fermentation technology.

Research

Research into the mechanisms of the fluidization process falls largely into two distinct categories: applied research, involving actual process plant or, more usually, laboratory units that seek to mimic the particular feature of the process plant that is the subject of study; and theoretical analysis, rooted in the rigorous framework of multiphase fluid mechanics. The former is the province of the engineer, the latter of the mathematician. Although instances of cross-fertilization have been known, such occurrences are rare. The theoretician who strays into the factory is appalled at the physical imponderables that characterize the real world, as is the engineer by the mathematical complexities in the analysis of a supposedly physical problem, even when it has been so simplified at the onset as to render it totally inapplicable to any conceivable practical application.

The analysis reported in this book is representative of a middle way that seeks to model the essential features of the fluidized state by imbedding in the basic theoretical framework (the conservation laws for mass and momentum) simple formulations of the primary force interactions, and drawing on formal analogies with theoretical treatments of simpler, well-posed physical problems possessing the same mathematical structure.

Single particle suspension

An obvious starting point for the examination of the mechanism of the fluidization process, which involves the suspension of a very large number of solid particles in an upwardly flowing fluid, is the much simpler case of the single particle.

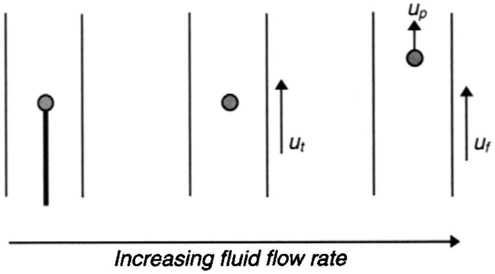

Figure 1.1 Single particle suspension and transport.

Consider a solid sphere sitting on a small support in a vertical tube (Figure 1.1, left). A fluid (either gas or liquid) is pumped up the tube so that it imparts an upward force on the sphere. As the fluid flow is progressively increased, this upward force reaches the critical value (at fluid velocity u_t) that just balances the sphere's weight; at this point the support structure can be removed and the sphere will remain stationary, supported entirely by the force of interaction with the fluid stream (Figure 1.1, middle).

If the fluid flow rate is now increased beyond this critical value u_t, the magnitude of the interaction force becomes greater than that due to gravity, giving rise to a net force that causes the sphere to accelerate upwards. As it does so, its velocity relative to the fluid (and, as a consequence, the interaction force) decreases progressively until it reaches the critical value at which the gravitational force is again just balanced:

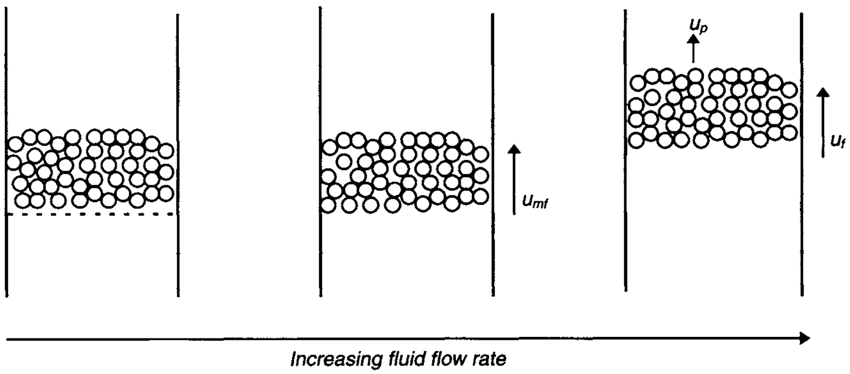

Figure 1.2 The minimum fluidization point.

$u_f - u_p = u_t$. From this point on the sphere continues its upward motion in equilibrium, at constant velocity u_p: $u_p = u_f - u_t$ (Figure 1.1, right).

We can try to apply these simple considerations, relating to a single solid sphere, to a bed consisting of a large number of such spheres supported on a mesh that extends over the entire tube cross-section (Figure 1.2). A progressive increase in the fluid flow rate will, once again, lead to the critical condition at which the total weight of the particles is just balanced by the fluid–particle interaction force (the *minimum fluidization* condition); at this point it could be thought possible to dispense with the supporting mesh, leaving the particle bed suspended motionless in the fluid stream, as was the case for the single sphere.

Continuing with the reasoning, we might expect a further increase in the fluid flow rate to cause the assembly of particles to accelerate upwards together, until such time as the relative velocity of the fluid ($u_f - u_p$) has fallen to that of the critical, minimum fluidization condition and equilibrium is re-established; from this point on the particle assembly would proceed up the tube, piston-like, at constant velocity.

Such behaviour, following the minimum fluidization point, does not occur in practice unless the particles are glued together. What precisely does happen is described in some detail in the following chapters, and depends on the properties of the particles and fluid involved. We will see that one possibility, commonly encountered when the fluidizing agent is a liquid, is that the bed 'expands' to an essentially homogeneous condition in which the particles are separated from one another more or less uniformly, with relatively little particle motion, the extent of the separation increasing progressively with increasing fluid velocity. Another possibility, more usually encountered with gas-fluidized systems, has already been mentioned: this time all the fluid in excess of that required to just bring the particles to the minimum fluidization point forms rising bubbles, which cause considerable particle mixing and give the bed the appearance of a boiling liquid. Various terms have been adopted to describe these two quite different manifestations of the fluidized state. We shall refer to them as *homogeneous* and *bubbling* fluidization respectively.

Fluidization quality

Homogeneous and bubbling fluidization represent two quite different fluid-dynamic environments brought about by the fluidization process itself. They may be regarded as somewhat extreme examples of *fluidization*

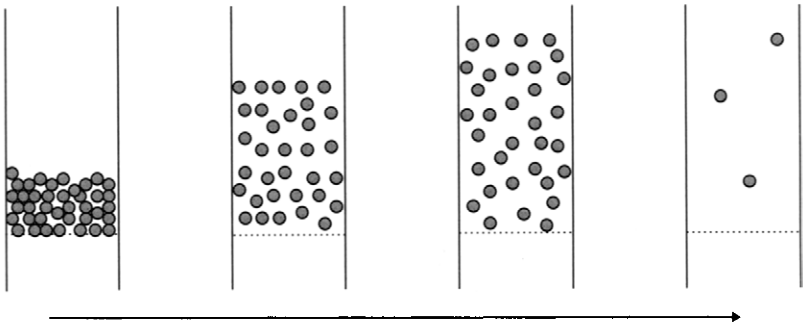

Figure 1.3 Homogeneous fluidization – from packed bed to single particle suspension.

quality, a conveniently vague term that nevertheless serves to portray the fluidized state as a continuous spectrum of behavioural conditions. Given that the main applications of fluidized bed technology rely on the provision of intimate contact between the solid and fluid phases for the purpose of promoting chemical reactions, it is hardly surprising that fluidization quality is a key factor in determining the performance of a fluidized bed as a chemical reactor. A major incentive for the analyses reported in the following chapters has been the urgent need for means of quantifying the essential factors that determine fluidization quality; and for predicting, on the basis of the particle and fluid properties and conditions of operation, the fluidization quality that would result in an envisaged fluidized bed reactor.

Homogeneous fluidization

The conceptually simplest means by which particles can remain in a bed, subjected to a fluid flux higher than that required for minimum fluidization, is for them to separate from one another so that the bed expands, the void space around the particles increases and, as a consequence, the fluid velocity within the bed decreases. This decrease in *interstitial velocity* has a strong effect on the fluid–particle interaction force, causing it to fall and thereby enabling a new equilibrium condition to be established in which the particle weight is once again just supported by the fluid. The mechanism just described represents the essential feature of *homogeneous fluidization.*

At first sight, there would appear to be no reason why any fluidized system should not be operated homogeneously at any fluid flow rate within the range bounded by the minimum fluidization velocity on the one hand and the velocity required to just support a single particle in the otherwise empty tube on the other. An equilibrium condition can always be identified within this range, but, as we shall see, other criteria must be satisfied in order for this condition to be attainable in practice. These considerations are best delayed until after the state of equilibrium itself has been examined.

Any analysis of the homogeneously fluidized state must encompass the conditions of single particle suspension and fluid flow through fixed beds of particles; these represent, respectively, the upper and lower bounds for fluidization as illustrated in Figure 1.3.

We start our examination of the fluidized state with brief accounts of established treatments of these upper and lower bounds. Both of these areas have been the subject of copious study, from which we select only those elements that are of direct relevance to the analysis that follows.