CHAPTER III

SPOUTED BED

3.1 Spouting of particulate solids

The spouted bed technique has become established in recent years as an alternative to fluidization for handling particulate solids, which are too coarse and uniform in size for good fluidization. Although the areas of application of spouted beds overlap with fluidized beds, the flow mechanisms in the two cases are different. Agitation of particles in a spouted bed caused by a steady axial jet and is regular and cyclic, as distinct from the more random and complex bubble-induced particle flow patterns in most fluidized bed.

Figure 3.1 shows a spouted bed schematically. Fluid (gas) is injected vertically through a centrally located small opening at the base of a conical, cylindrical or conical-cylindrical vessel containing relatively coarse particulate solids. If the fluid injection rate is high enough, the resulting jet causes a stream of particles to rise rapidly through a hollowed central core, or spout, within the bed of solids. These particles, after rising to a height above the surface of the surrounding packed bed, or annulus, rain back as a fountain onto the annulus, where they slowly move downward and, to some extent, inward as a loosely packed bed. Fluid from the spout leaks into the annulus and percolates through the moving packed solids there. These solids are re-entrained into the spout over the entire bed height. The overall system thereby becomes a composite of a centrally located dilute-phase co current-upward transport region surrounded by a dense-phase moving packed bed with countercurrent percolation of fluid. A systematic cyclic pattern of solids movement is thus established, with effective contact between fluid and solids, and with unique hydrodynamics.

The spouted bed regime, which occurs over a limited range of fluid velocity, is bracketed fixed packed bed operation at the lower velocities and by bubbling or slugging fluidized bed operation at the higher. For a given combination of fluid, solids and vessel configuration, the transitions between regimes can best be represented quantitatively by plots of bed depth versus fluid velocity. An example of such a plot (phase diagram) is given in Figure 3.2. The demarcation line obtained by decreasing the fluid velocity until the spout collapses to give a static bed in its random loose-packed condition represents the minimum spouting velocity, u_{ms}, at various bed depths. The horizontal transition line separating spouting and bubbling represents the maximum spoutable bed depth, H_m, for the given system.

3.2 Requirements for spouting

Spouting, which is a visually observable phenomenon, occurs over a definite range of gas velocity for a given combination of gas, solids, and vessel configuration. Figure 3.3 illustrates the transition from a quiescent to a spouting to a bubbling to a slugging bed, which often occurs as gas velocity is increased. These transitions can be represented quantitatively as plots of bed depth versus gas velocity, or phase diagrams, examples of which are given in Figure 3.3.

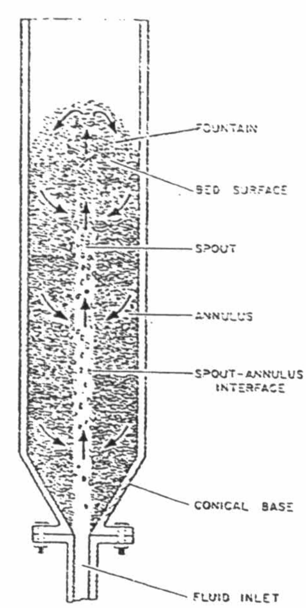

Figure 3.1 Schematic diagram of a spouted bed

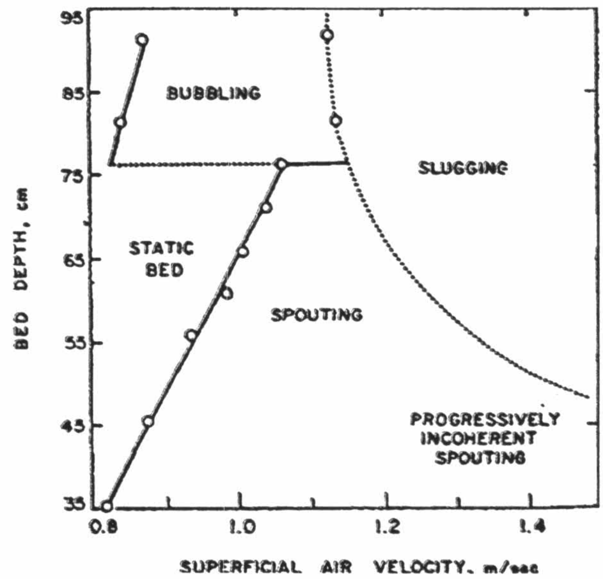

Figure 3.2 Phase diagram for wheat particles (prolate spheroids: 3.2 mm x 6.4 mm, ρ_p =1,376 kg/m^3), diameter of vessel =152 mm., diameter of inlet gas=12.5 mm

The line representing transition between a static and an agitated (spouted or fluidized) bed is more reproducible in the direction of decreasing velocity than vice versa, the resulting static bed being in the reproducible random loose packed condition. Figure 3.4 shows that, for a given solid material contacted by a specific fluid in a vessel of fixed geometry, there exists a maximum spoutable bed depth H_m, beyond which spouting action does not occur but is replaced by poor quality fluidization. The minimum spouting velocity at this bed depth can be up to 50% greater than the corresponding minimum fluidization velocity u_{mf}, though closer correspondence between these two critical velocities has usually been found and for analytical purposes it has sometimes been convenient to equate them. Phase diagrams of Figure 3.4 also indicate that for given solids, gas, and column diameter, there is a maximum gas inlet size beyond which spouting does not occur, the bed changing directly from the quisecent to the aggregatively fluidized state.

A typical spouted bed has a substantial depth, which in the case of a cylindrical vessel is usually of the order of at least one column diameter, measured from the inlet orifice to the surface of the annulus. If the bed is much shallower, the system becomes hydrodynamically different from true spouting, and any generally formulated principles of spouted bed behaviour would not be expected to apply. A minimum spoutable depth has not been precisely defined or investigated. Nor have any detailed studies been made about the maximum spouting velocity, at which transition from coherent spouting to either bubbling fluidization or slugging occurs.

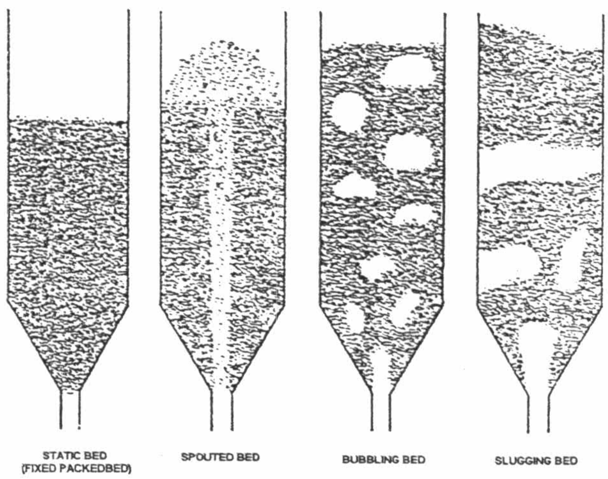

Figure 3.3 Phase transition with increasing gas flow

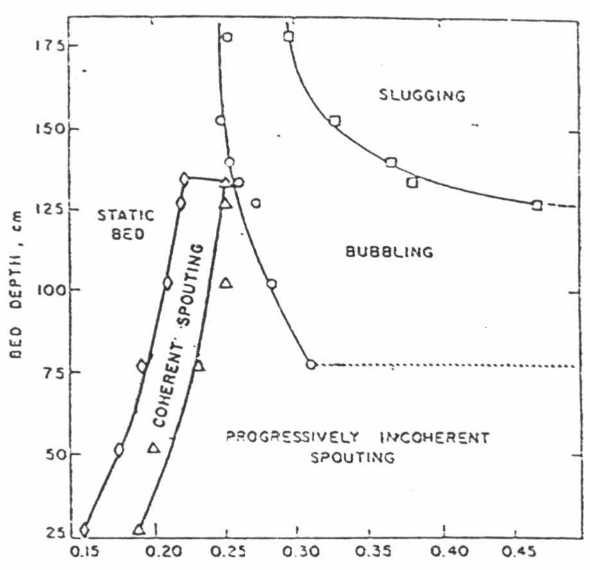

Figure 3.4 Phase diagram of sand(d_p =0.42-0.83 mm, diameter of column = 15.2 cm, diameter of inlet gas = 1.25 cm)

3.3 Onset of spouting

The mechanism of transition from a static to a spouted bed is best with a plot of bed pressure drop versus superficial velocity as shown in Figure 3.5. The plot for the deepest bed (ABCD) is supplemented by a dashed curve (DC′B′A) illustrating the reverse process, that is the collapse of a spouted bed on decreasing the gas velocity.

The sequence of events is observed as the gas flow is increased as follows:

1) At low flow rates the gas simply passes up without disturbing the particles, the pressure drop rising with flow rate (along AB) as in any static packed bed.
2) At a certain flow rate, the jet velocity becomes sufficiently high to push back the particles in the immediate vicinity of the gas inlet, causing a relatively empty cavity to form just above the inlet. The particles surrounding the cavity are compressed against the material above, forming a compacted arch which offers a greater resistance to flow. Therefore, despite the existence of a hollow cavity, the total pressure drop across the bed continues to rise.
3) With further increase in gas flow, the cavity elongates to an internal spout. The arch of compacted solids still exists above the internal spout so that the pressure drop across the bed rises further until it reaches a maximum value - ΔP_M, at point B. The corresponding superficial velocity is denoted by u_M.
4) As the flow rate is increased beyond point B, the height of the relatively hollow internal spout become large in comparison with the packed solids above the spout. The pressure drop therefore decreases along BC.
5) As point C is approached, enough solids have been displaced from the central core to cause a noticeable expansion of the bed. This bed expansion sometimes results in arresting the fall in pressure drop (though there is little such tendency exhibited in the curves of Figure 3.6), and is usually accompanied by alternate expansion and contraction of the internal spout. The resulting instability gives rise to pressure drop fluctuations and for deeper beds, to fluidization of the particles above the internal spout.
6) With only a slight increase in flow rate beyond point C, which is called the point of incipient spouting, the internal spout breaks through the bed

surface. When this happens, the solids concentration in the region directly above the internal spout decrease abruptly, causing a sharp reduction in pressure drop to point D, at which the entire bed becomes mobile and steady spouting sets in. Point D thus represents the onset of spouting.

7) With still further increase in gas flow, the additional gas simply passes through the spout region, which is now established as the path of least resistance, causing the fountain to shoot up higher without any significant effect on the total pressure drop. The pressure drop $-\Delta P$ beyond point D therefore remains substantially constant.

The incipient spouting velocity (C) and the onset of spouting (D) are not exactly reproducible. A more reproducible velocity, the minimum spouting velocity u_{ms}, is obtained by slowly decreasing the gas flow: the bed then remains in the spouted stste until point C', which represents the minimum spouting condition. A slight reduction of gas velocity at this condition causes the spout to collapse and the pressure drop to rise suddenly to point B'. Further diminution of flow rate causes pressure drop to decrease steadily along $B'A$. However; the main curve now falls lower than for increasing flow since the energy required by the gas jet to penetrate the solids is no longer expended during the collapse of the spout. The hysteresis loop $ABCDC'B'A$ can be shrunk somewhat if the process is repeated starting with a loose rather than a relatively dense packed bed, but it cannot be eliminated entirely due to the inherent irreversibility of the jet penetration phenomenon.

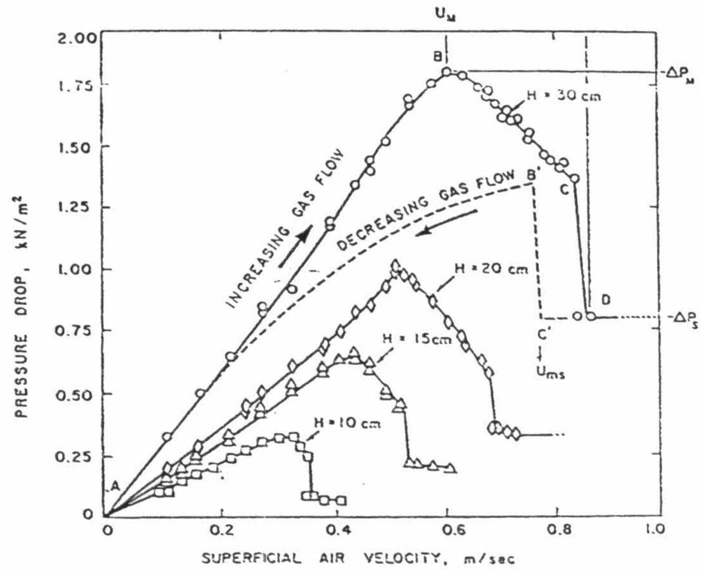

Figure 3.5 Typical pressure drop-flow rate curves (Wheat: d_p = 3.6 mm, diameter of column =15.2 cm, diameter of inlet gas = 1.27 cm, θ = 60.

3.4 Minimum spouting velocity

For cylindrical vessels up to 0.6 m in diameter, with or without a conical base, the Mathur-Gishler equation (1955) continues to be the most reliable predictor (within $\pm$10 %) of the minimum spouting velocity for a wide variety of solid materials, bed dimensions, nozzle diameters, and fluids ranging from air to water. The correlation is:

$$u_{ms} = \left(\frac{d_p}{D_c}\right)\left(\frac{D_i}{D_c}\right)^{1/3}\sqrt{\frac{2gH_m(\rho_p - \rho_f)}{\rho_f}} \tag{3.1}$$

where the particle diameter, d_p, is taken as the arithmetic average of bracketing screen apertures for closely sized near spherical particles and as the volume-surface mean diameter for mixed sizes, using the equivolume sphere diameter d_p for nonspherical particles. For bed diameter exceeding 0.6 m, Equation (3.1), which can be rationalized qualitatively by jet-to-particle momentum transfer considerations, increasely underestimates u_{ms}.

3.5 Solid circulation rate

The solids circulation rate in conical spouted bed can be estimated if the particle velocity above the cone and the particle voidage are known either in the spout or in the downcomer. Many investigators have followed the latter procedure to estimate the solids circulation rate because the particle velocity at the wall and the voidage are easily estimated for the downcomer (Mathur and Epstein 1974). The particle velocity in the downcomer is measured by tracking the particles in the cylindrical portion of the bed. The solids circulation rate may be expressed as:

$$W_s = A_d v_p \rho_p (1 - \varepsilon) \qquad (3.2)$$

where $W_s, A_d, v_p, \rho_p, \varepsilon$ are particle circulation rate, cross-sectional area of downcomer, particle velocity above the slanting base, particle density and voidage respectively.

The studies in cylindrical spouted beds have shown that there are significant effects of particle shape and surface characteristics on the solids circulation. A regular pattern of solid flow may not be possible if the spouting material is rough or sticky or includes impurities that may cause channeling of solids and dead zones above slanting base. Even the size distribution of particles can affect the spouting of a bed. However, these effects are difficult to evaluate and quantify.

3.6 Applications of spouted bed

Originally developed for wheat drying, gas-spouted beds have been applied to a wide variety of operations involving coarse (e.g. 1-5 mm) solid particles. These operations rely on one or more of the following features of the technique:

1) Good solids mixing coupled with satisfactory gas-particle contact such as the ability to accomplish for coarse solids what a fluidized bed does for fine solids.
2) Higher gas velocities and correspondingly lower gas residence times than for conventional fluidized beds of fine solids.
3) Systematic cyclic movement of solids, compared with the more random particle movement in other systems such as fluidized beds or rotary drums.
4) Solids deagglomeration and attrition caused by the high velocity interparticle collisions in the spout.

5) The absence of a distributor plate, in contrast to the case of a fixed or fluidized bed.

- Good solids mixing, along with effective gas particle contact, is the basis for spouted bed drying of noncaking granular solids. The method is particularly suitable for heat-sensitive materials such as agricultural products or polymer granules, since the rapid agitation of the solids permits the use of higher temperature gas than in nonagitated driers, without the risk of thermal damage to the particles.

Sensible heating or cooling of coarse solids in spouted beds also makes use of the favorable gas-solid contacting, but the good solids mixing is more important in heating than in cooling.

- The relatively high gas velocities and correspondingly low gas residence times associated with spouting of coarse particles are the basis for the bench-scale development at Hokkaido University of a dual-spouted reactor-regenerator combination for the thermal cracking of petroleumn feedstocks.

- The highly systematic cyclic movement of solids in a spouted bed has proved to be a key advantage in such processes as granulation and particle coating. In granulation, a melt or solution is atomized into a bed containing seed granules spouted by hot gas. These granules build up by a mechanism of layer-by-layer growth as they cycle in the bed, and yield a final product which is well-rounded and uniform in structure. The coating of pharmaceutical tablets in a spouted bed is a well-established commercial operation. The principle of spouted bed granulation can also be used for coating of particles. The coating unit operation consists in loading a batch of the tablets to be coated into the column, turning on the hot air supply to spout the bed, and then starting the flow of the preheated coating liquid through the pneumatic atomizing nozzle. The rate of liquid flow is regulated that the spouting action is not impaired due to stickiness caused by excessive surface moisture on the tablets. After the desired quantity of coating solution has been supplied to the bed, a period of drying to remove any residual solvent from the coating is allowed at a reduced airflow rate with the bed in quiescent condition. Since drying of the solution during the coating operation occurs almost instantaneously, there is little danger of solvent penetration into the tablet core, and therefore the final drying of the coated batch takes only a few minutes.

- The solids attrition caused by the particle collisions in the spout is a liability for some spouted bed operations such as granulation, tablet coating, but is an asset for several others. The most successful of these, developed at the Leningrad Institute of Technology, is the drying of suspensions and solutions by atomizing them into the lower region of a hot gas spouted bed of inert particles. The suspension or solution coats these particles and dries during the particle downward movement in the annulus. The fine product is broken away by interparticle collisions in the spout and collected from the overhead gas. Materials, which lend themselves to this method of drying, include organic dyes, dye intermediates, lacquers, salt and sugar solutions, and several chemical reagents.

- The absence of a distributor plate in a spouted bed is a definite advantage in granulation and coating, in drying of solutions, suspensions and sticky solids, and in cabonization or gasification of caking coal. It is also an important consideration in a high temperature (1,300-1,800 K) industrial process for making granular activated carbon.

3.7 Modified spouted beds

3.7.1 Draft tube

Cross-flow of both fluid and solids between the spout and the annulus can be eliminated over most of a spouted bed's height by interesting in the spout region, starting at some distance above the fluid inlet nozzle, an open draft tube with walls that are impervious to both phases. The draft tube diameter is usually chosen to be similar to that of the spout which occurs without a draft tube. The draft tube is aligned vertically with its axis collinear with the axis of the column. One result is that the bed can function at depths greater than maximum spoutable bed height. Other consequences are a large reduction in the fluid flow requirement for spouting, an even larger reduction in the solids circulation rate, and considerably reduced solid mixing. These changes could be advantageous for granulation and particle coating, where plug flow of solids should increase the uniformity of the product. The method also reduces the size of solids that can be successfully spouted.

3.7.2 Top-Sealed Vessel

By sealing the top of the spouting vessel and providing an alternative fluid outlet either at the bottom of the bed or part way below the bed surface (Figure 3.6), the spout fluid is forced to travel downward through the annulus. This results in a narrower range of fluid residence time distribution than otherwise. The residence time distribution can be further narrowed if, in addition, an inner draft tube is used. The combination of side outlet and draft tube appears to give high gas conversions and great versatility in operable particle sizes.

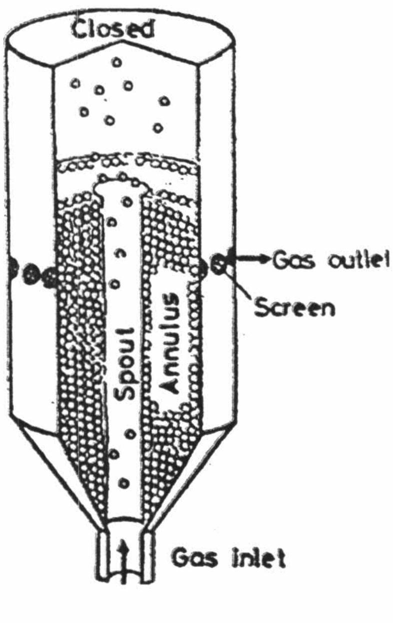

Figure 3.6 Schematic diagram of a top-sealed spouted bed with side wall gas outlet

3.7.3 Spout-Fluid Bed

If, in addition to supplying spouting fluid through a centrally located inlet nozzle, sufficient extra fluid is also supplier through either a flat or a conical (Figure 3.7) distributor to fluidize the annulus fluid solids, the result is a spouted-fluidized or spout-fluid bed. The total fluid flow required for spout-fluidizing a given bed exceeds that for either spouting it or fluidizing it, but the extra fluid may be well spent, since such a bed displays more vigorous solids agitation in the annulus than a standard spouted bed and a greater deagglomeration tendency than a conventional fluidized bed.

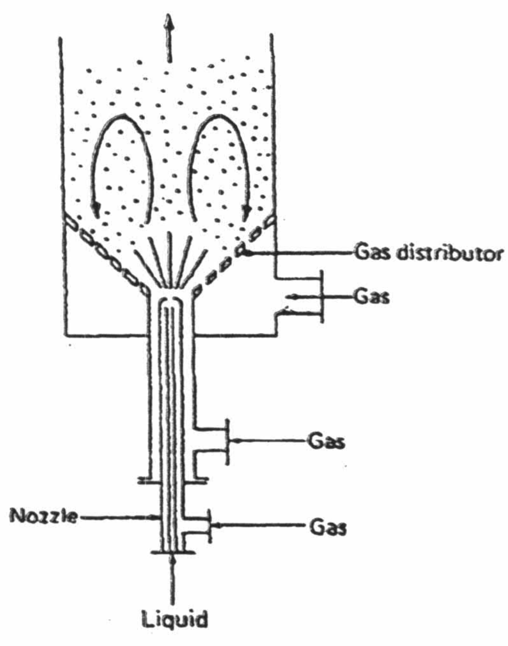

Figure 3.7 Conceptual diagram of a three-phase spout-fluid bed with cocurrent flow of gas and liquid