A TECHNIQUE FOR CONTACTING GASES WITH COARSE SOLID PARTICLES

K. B. Mathur and P. E. Gishler
National Research Council of Canada, Ottawa

Although coarse, uniformly sized particles are not amenable to fluidization, it has been found possible by use of either gases or liquids to impart a regular cycling motion to a bed of this type of material in which the solids are rapidly carried upward by the fluid in a central well-defined core within the bed. The particles move uniformly downward in the annular space surrounding the core, thus providing dense-phase countercurrent contact between the fluid and the solids. There is no wall separating the core from the annulus. This method is called the spouted-bed technique. The effect of column diameter, fluid inlet diameter, bed depth, and physical properties of solids and fluids on spouting behavior has been investigated. The minimum fluid velocity required for spouting has been correlated, and the flow pattern of the fluid and of the solids has been studied. The technique has been applied to the drying of wheat.

FIG. 1. SPOUTED WHEAT BED IN A 6-IN. SECTIONAL COLUMN.

Fluidization of solids has proved to be a useful technique for vapor-solid contact. The reasons for its wide acceptance and application are certain unique characteristics which are inherent in the system, viz., ease of transferring solids to and from vessels, uniformity of conditions such as temperature, etc., within the bed, and high heat and mass transfer rates associated with the system. Application has, however, been limited to relatively fine solids because coarse materials when subjected to fluidization show a marked tendency toward slugging (*4, 7*). This paper describes a technique—called the spouted-bed technique—which has been developed for effectively handling coarse particles. The mechanism of flow of solids as well as of gas in this technique is different from fluidization, but it appears to achieve the same purpose for coarse particles as fluidization does for fine materials. Whereas the major application of the technique is believed to be for coarse particles, it was found to work effectively for solids as fine as 20 to 35 mesh which are also capable of being fluidized. Thus there is a slight overlap between spoutable and fluidizable sizes.

DESCRIPTION OF THE SPOUTED-BED TECHNIQUE

If coarse solid material is poured into a cone-bottomed column having a small central opening for air inlet at the base of the cone and subjected to an increasing upward air flow, the following steps will occur. At low air velocities the air will simply pass upward through the solids bed without disturbing the particles; however, as the air velocity is increased, a point will be reached when there is a noticeable readjustment of the particles. A further increase in air flow causes a stream of solids to rise rapidly as a central core, or spout, within the bed. The solids in the spout, having reached somewhat above the bed level, fall back onto the annular space around the spout and travel downward uniformly as a packed bed. Thus a spouted bed is a composite of a central air spout carrying the solids upward and a downward-moving annulus with a countercurrent flow of air. A considerable cross flow of solids from the annulus into the spout takes place all along the bed height. Figure 1 illustrates a spouted bed of wheat in a sectional column; Figure 2 indicates the solids-flow pattern schematically.

The effect of air flow on bed condition is illustrated by the pressure drop across the bed. A typical pressure-drop curve is shown in Figure 3. With increasing air velocities the pressure drop rises directly to point *B*, as would be expected in a packed bed. Increasing the air flow beyond this causes a sharp decrease in pressure drop to the point at which the air velocity at the inlet becomes high enough to lift the particles at the base of the cone and thus form a short internal spout in that region. With further increase in air flow this spout increases in height until at point *C* enough solids have been displaced from the central core to cause a noticeable expansion of the bed. At an air-flow rate corresponding to point *D*, movement of particles at the top of the bed is observed, but the spout is still confined to the lower part of the bed. Increasing the air flow beyond this point causes a sharp decrease in the pressure drop to point *E*, where the spout breaks through the top of the bed and steady spouting sets in. Beyond this point the pressure drop decreases only slightly with an increase in air flow.

If the air flow is then decreased, the bed stays in the spouted condition until an air velocity corresponding to point E' is reached, which is somewhat lower than the velocity at point E. This is made possible because the energy for breaking interparticle contacts in the central core is no longer necessary as is the case with increasing air flow. Point E' represents the minimum air flow for spouting; a slight reduction in air flow at this stage results in a sharp rise in the pressure drop owing to the collapse of the spout. The bed behaves like a packed bed beyond this point, the curve for decreasing air flow being lower because the particles are loosely packed.

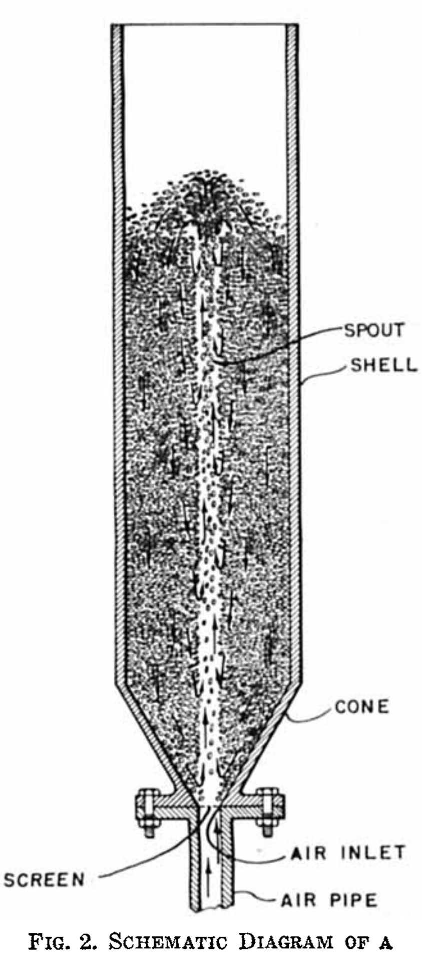

Fig. 2. Schematic Diagram of a Spouted Bed.

CONDITIONS NECESSARY FOR SPOUTING

Conditions, viz., inlet-air diameter, air-flow rate, bed depth, and particle size, necessary for spouting are critical. For a certain particle size and column diameter there is a maximum inlet-air size beyond which spouting does not take place. The maximum bed depth to which a certain material can be made to spout is also limited and depends upon the column diameter and the size of the inlet-air opening.

Figures 4 and 5, which are phase diagrams for —20+35-mesh Ottawa sand, quantitatively illustrate the critical nature of the inlet-air diameter, air flow, and bed depth on spouting. For the data represented in Figure 4, a 1/2-in. standard pipe was used for the inlet air at the bottom of an 85° (included) angle cone, which formed the base of a 6-in. glass column. An increase in air flow caused the transition of the sand bed from packed to fluidized with further increase resulting in slugging. However, when the size of the air inlet was reduced to a 3/8-in. standard pipe (Figure 5), a bed as deep as 27.0 in. could be made to spout. Good spouting was achieved only over a narrow range of air flow; increasing the air rate above a certain value resulted in fluidizing and finally slugging. A bed deeper than 27 in. did not spout but changed directly from a packed to a fluidized bed with increasing air flow.

A similar phase diagram for wheat, in a 6-in. column with a 3/8-in. standard pipe for air inlet, is depicted in Figure 6. The range of air flow for spouting is considerably wider with wheat than with sand.

SCOPE OF INVESTIGATION

This work was conducted with two main objects in view: (1) to gain an insight into the mechanism of gas and solids flow in a spouted bed and (2) to study the effect of the major variable of the system on spouting behavior.

MECHANISM OF GAS AND SOLIDS FLOW

The flow characteristics of such a system are of importance in understanding and properly applying the technique. In order to arrive at a complete picture of the flow mechanism, the following characteristics have to be studied: flow of gas through annulus and through spout, flow of solids through annulus and through spout, void space in annulus and in spout.

Experimental

Considerable data have been taken for different solids with varying column diameters, bed depths, and air-inlet sizes. For explaining the flow mechanism, a 25-in.-deep wheat bed in a 6-in.–diam. column with a 3/8-in. standard pipe for air inlet at the base of an 85° cone has been chosen as a typical spouted bed. The choice of this system is arbitrary, and a study of the effect of column design, solids properties, and fluid properties on flow mechanism has not been attempted. The following discussion is confined to the typical system described above.

Flow of Air. The data taken to establish the flow pattern of air in a spouted bed consist of vertical static-pressure-drop profiles. The radial pressure-drop gradient was found to be negligible. A single pressure probe consisting of 1/8-in. Shelby tubing with 1/64-in. static pressure holes, and a water-air manometer were used for taking the pressure-drop data. Readings were usually taken every 4 in. along the bed height; all observations were taken above the cone, which extends 5 in. above the air inlet. Pressure-drop measurement, as an indication of air flow, was considered preferable to direct measurement of air velocity because of the usual difficulties encountered as a result of solids interference (*6*).

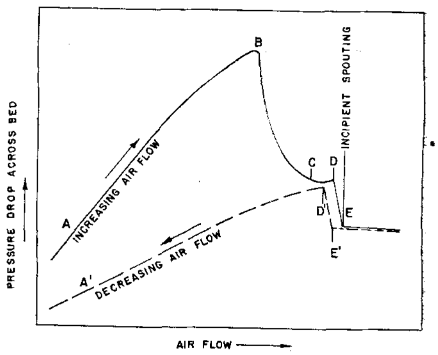

Fig. 3. Effect of Air Flow on Pressure Drop in a Bed of Solids Using a Small Central Air Inlet.

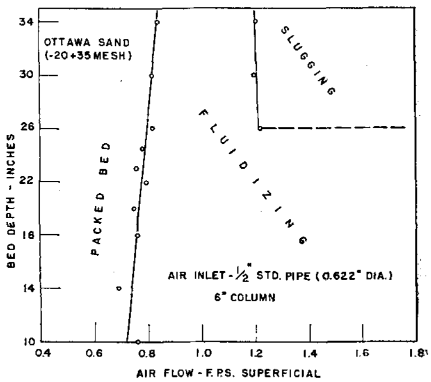

Fig. 4. Phase Diagram for Sand, 1/2-in. Standard Pipe for Air Inlet.

Flow of Solids. It is not possible to obtain information on the upward velocity of particles in the spout in the circular column because the spout is not open to view. A sectional 6-in.–diam. Plexiglass column was built in which the spout is visible along the flat side (Figure 1). The inlet-air opening for this column was a 0.493-in.–diam. (equivalent to a 3/8-in. standard pipe) half circle.

It is doubtful whether the half column is a true representation of the full column, as interference is caused by the introduction of a flat wall; however, the relative flow behaviors in the half column should be comparable to those in the full column. This view is supported by the fact that the shapes of the particle velocity-at-wall and pressure-drop profiles for the half and full columns are identical (Figures 7 and 8). While use has been made of the information obtained on the half column for flow explanations in the full column, it has been kept in mind that only the relative behaviors in the half column are significant.

To obtain data on particle velocity in the spout in the half column, high-speed motion picture technique was employed. A Western Electric Fastax 16-mm. camera was used to take motion pictures of the spout at 3,000 frames/sec. Colored wheat particles were dropped in the bed to serve as indicators. Close-up shots from about 5 ft. were taken on 100 ft. rolls so that the movement of the particles might be distinctly traced. Projecting the movies in slow motion made it possible to measure particle velocities in the spout at different levels. Data were also taken to measure vertical profiles of the particle velocity at the column wall. This was done simply by timing the particles across 4-in. increments along the bed height. The observations were fairly reproducible; an average of a dozen readings across each increment of height has been reported. The particle velocities did not vary along the column periphery.

Results and Discussion

Flow of Air. *Annulus.* The annulus in a spouted bed is a downward-moving bed of solids. The expansion in the bed was observed to be about 6%, which is roughly equivalent to the volume of the solids displaced from the spout, and indicates that the annulus is substantially a packed bed. Visual observation verifies this. The pressure drop along the bed height is, therefore, a measure of the loss of energy of the air flowing through it, and the situation is similar to the flow of gas through a loosely packed bed.

In order to arrive at the air flow through the annulus, a pressure-drop vs. airflow curve for a packed bed was first determined experimentally. These data were obtained in a 6-in. glass column by use of a sintered stainless steel grid as an air distributor. Static pressure-drop readings were taken at different air-flow rates including rates high enough to cause agitation of the bed.

Figure 9 gives ΔP as a function of superficial air velocity; the lower curve is for loose packing. Figure 8 is the vertical pressure-drop profile in a spouted bed. For a certain value of pressure drop in the spouted bed, the superficial air velocity in the annulus is equal to that indicated by the curve for a loosely packed bed.

The air velocity in the annulus has been worked out on this basis and plotted in Figure 11 against bed level. To obtain the volumetric air flow from the superficial velocity, the cross-sectional area of the annulus and therefore the diameter of the spout along the bed height must be known. This was measured in a 25-in. spouted bed of wheat in the half-sectional column. The spout diameter was 1.1 in. at a level of 2 in. from the inlet; it increased rapidly to 1.4 in. at the 6-in. level and then gradually to 2 in. at the top of the 25-in.-deep bed. In the full column it was possible to estimate the spout diameter at the bed top as 2 in. which agrees with the spout diameter at bed top in the half column; hence it is assumed that the spout diameters at different bed levels in the half and full columns are identical. Since the variation in spout diameter along bed height is relatively small, the over-all flow picture would not be significantly affected even if this assumption were not strictly true. The volumetric flow in the annulus as a percentage of total flow is also contained in Figure 10. From this it can be seen that the air steadily flares out from the spout into the annulus as it rises up the bed; this tendency is much more pronounced in the lower part of the bed, as is evident from the rapid change in slope of the curve for this region. Near the top of the bed almost two thirds of the total air flows through the annulus.

It is interesting to note that the maximum air velocity in the annulus at the top of the bed is approximately the velocity required to fluidize wheat, as indicated in Figure 9.

Spout. The air flow through the spout has been worked out for different bed levels by taking differences between the total air flow and the air flow through the annulus. Results are plotted in Figure 11 as the percentage of total flow through the spout against bed level. Based on the diameters of the spout, the superficial air velocity through the spout has been calculated and plotted in the same figure. The air enters the bed at a high linear velocity; about 30% of it flares out into the annulus during its travel through the cone, and at the same time the core diameter increases to about 1.4 in., reducing the velocity through the spout at the top of the cone to 50 ft./sec. The lateral flow of air from the spout to the annulus is gradual

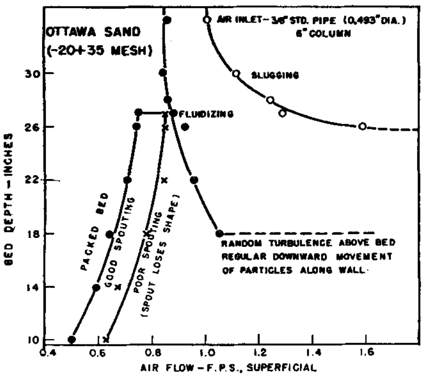

Fig. 5. Phase Diagram for Sand, 3/8-in. Standard Pipe for Air Inlet.

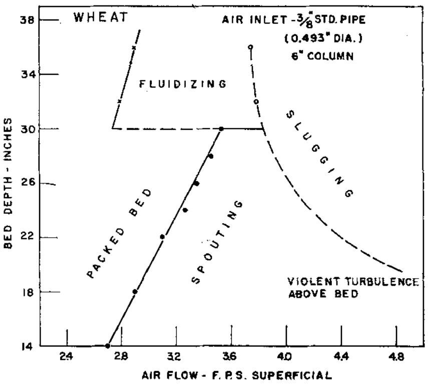

Fig. 6. Phase Diagram for Wheat, 3/8-in. Standard Pipe for Air Inlet.

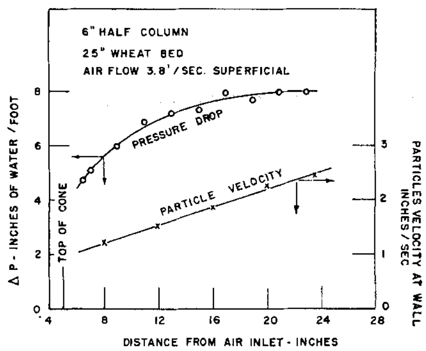

Fig. 7. Pressure Drop per Foot and Particle Velocity at Wall vs. Bed Level (Half Column).

above the cone, the velocity falling off to 13.5 ft./sec. at the top of the bed.

Flow of Solids. *Annulus.* The particle velocity at the column wall should be an indication of the downward flow of solids in the annulus. The particles gradually slow from 2.62 in./sec. at the top of the bed to 1.74 in./sec. at a level of 10 in. from the base of the column (Figure 8), indicating that there is a steady cross flow of solids

Figure 13. The particles which enter the spout at the bottom receive a sudden impulse from the high-velocity stream of air and accelerate rapidly from rest to a maximum velocity of about 25 ft./sec. at a level of 7 in. from the air inlet. As they travel further up the bed, they transfer part of their kinetic energy to the particles which enter the spout from the annulus, thereby accelerating them from rest to the average particle velocity in the spout at that level.

initial energy imparted to the particles by the air in the cone. The experimental points on Figure 13 are for the half column with a total superficial air velocity of 3.8 ft./sec. In the full column the air velocity used was 3.72 ft./sec. Theoretical considerations based on drag coefficients indicate that the rising part of the particle-velocity curve for the full column should be slightly lower than the curve for the half column(*1*). The falling part of the curve would not be

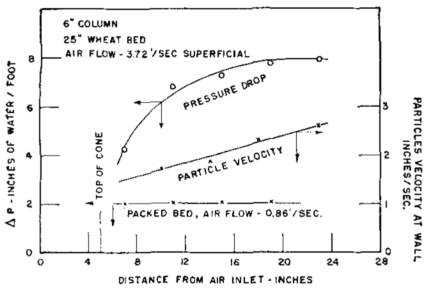

FIG. 8. PRESSURE DROP PER FOOT AND PARTICLE VELOCITY AT WALL VS. BED LEVEL (FULL COLUMN).

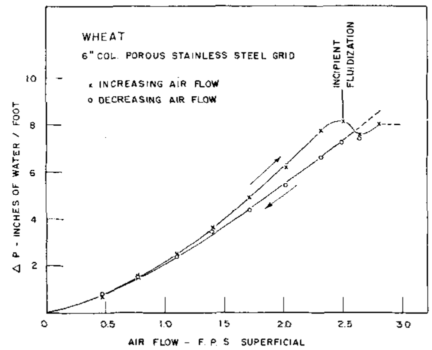

FIG. 9. PRESSURE DROP PER FOOT VS. AIR FLOW USING A UNIFORM AIR DISTRIBUTOR.

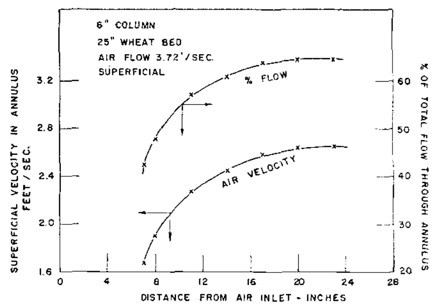

FIG. 10. AIR FLOW THROUGH ANNULUS VS. BED LEVEL.

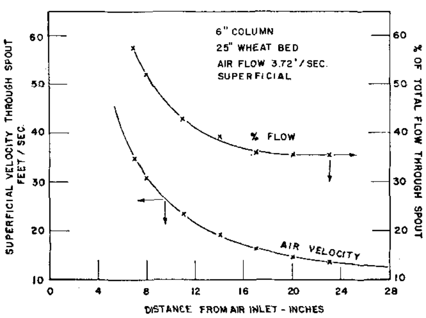

FIG. 11. AIR FLOW THROUGH SPOUT VS. BED LEVEL.

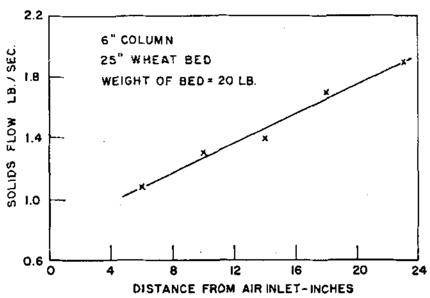

FIG. 12. SOLIDS FLOW IN ANNULUS VS. BED LEVEL.

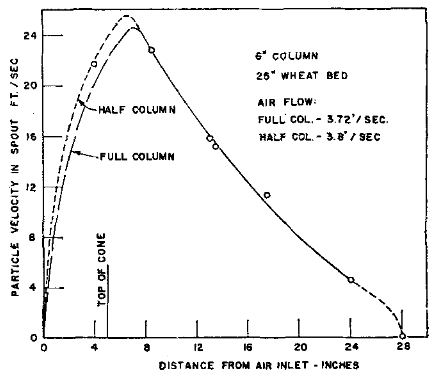

FIG. 13. PARTICLE VELOCITY IN SPOUT VS. BED LEVEL.

from the annulus into the spout along the bed height. Observations made on the flat side of the half column show that the radial gradient of particle velocity in the annulus is not appreciable; in other words, the solids in the annulus as a whole are moving downward at velocities indicated at the column wall. The flow of solids in the annulus, worked out on this basis, is plotted in Figure 12.

Spout. Data obtained from high-speed motion pictures of the spout for the half column are shown in

Owing to this constant transfer of energy along the bed height, the over-all particle velocity in the spout rapidly falls off until it reaches zero at a level of 28 in. from the air inlet, a point 1 1/2 in. above the bed level, at which the particles reverse their direction. Superimposed on this effect is the lifting action caused on the particles by the upflowing air in the spout. However, since the air velocity in the spout drops off sharply above the cone, this is estimated to be small compared with the

significantly altered by differences in air-flow rates used in the half and full columns.

Void Space. *Annulus.* The annulus in a spouted bed is considered similar to a loosely packed bed. The void space for such a bed of wheat, calculated from the measured bulk and absolute densities, equals 43.2%.

Spout. The downward solids flow in the annulus should equal the upward solids flow in the spout at any bed level since spouting is a steady-state flow system. The solids flow in the annulus has been worked out from the data on particle velocity at wall. Knowing the upward linear velocity of the particles in the spout, the authors calculated the bulk density and void space in the spout, the latter being plotted in Figure 14.

It has been found possible to calculate the void space in the spout from the pressure drop data as well. The spout can be compared to a vertical riser through which

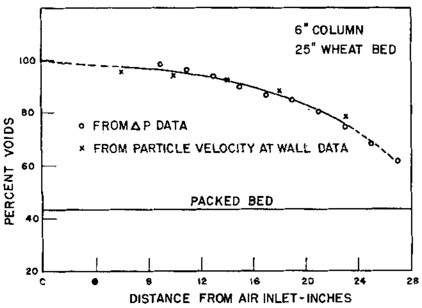

FIG. 14. VOID SPACE IN SPOUT VS. BED LEVEL.

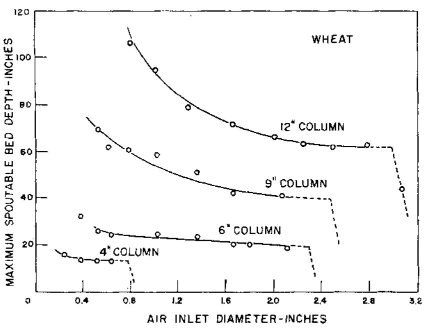

FIG. 15. EFFECT OF AIR INLET DIAMETER ON MAXIMUM SPOUTABLE BED DEPTH.

solids are being transported by a stream of air. The pressure drop under such conditions is composed of (2, 7) (a) a solids static head equivalent to the dispersed-solids density, (b) a solids friction loss due to contact of particles with air and with the pipe wall (the pipe in this case may be visualized as made of wheat particles), and (c) an acceleration pressure drop. In mathematical terms

$$dP_{total} = dP_{friction} + dP_{acceleration} + dP_{weight}$$

$$dP_T = dP_{f+a} + dP_w \qquad (1)$$

When an incremental height of spout dh is considered, one may let the solids flow across $dh = m$ lb./sec., the solids velocity across $dh = v_p$ ft./sec., the cross-sectional area of the spout $= A$ ft.; then kinetic energy associated with the solids at any point

$$= \frac{1}{2g} \cdot mv_p^2 \qquad (2)$$

Change in kinetic energy across $dh =$

$$d\left(\frac{1}{2g} \cdot mv_p^2\right) = \frac{1}{2g} \cdot d(mv_p^2) \qquad (3)$$

If the average air velocity through the spout across $dh = v_a$ ft./sec. then the energy loss from air to solids across $dh =$

$$d\,(v_a \,.\, A \,.\, P_{f+a}) = v_a \,.\, A \,.\, dP_{f+a} \qquad (4)$$

when air velocity and spout diameter are assumed to be constant across dh and substantially equal to the average values for the increment; dh has been taken small enough so that this assumption is valid.

Energy gained by the solids = energy lost by the air or

$$\frac{1}{2g} \cdot d\,(mv_p^2) = -\, v_a A \,.\, dP_{f+a} \qquad (5)$$

changes in heat energy, potential energy, etc., being neglected.

$$dP_{f+a} = -\frac{1}{2g.v_a.A} \cdot d\,(mv_p^2) \qquad (6)$$

It is known that

$$dP_w = d\,(\rho_b \,.\, h) \qquad (7)$$

where ρ_b = bulk density in spout, lb./cu.ft.

Dividing Equation (6) by Equation (7) gives

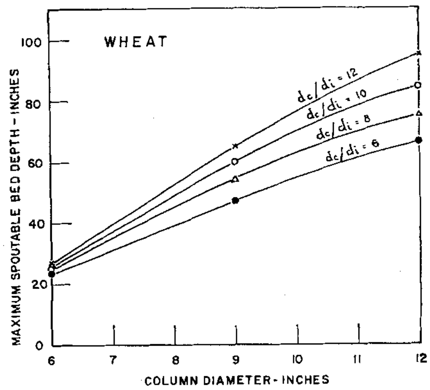

FIG. 16. EFFECT OF COLUMN DIAMETER ON MAXIMUM SPOUTABLE BED DEPTH.

$$\frac{d.P_{f+a}}{dP_w} = -\frac{d(mv_p^2)}{d(\rho_b.h)} \cdot \frac{1}{2g.v_a.A} \qquad (8)$$

$$m = v_p \cdot A \,.\, \rho_b \qquad (9)$$

Substituting Equation (9) in (8) gives

$$\frac{dP_{f+a}}{dP_w} = -\frac{d(v_p^3 \,.\, \rho_b)}{d(\rho_b \,.\, h)} \cdot \frac{1}{2g \,.\, v_a} \qquad (10)$$

TABLE 1.—SPOUTING BEHAVIOR OF VARIOUS MATERIALS, 6-IN.-DIAM. GLASS COLUMN, 3/8-IN. STANDARD AIR INLET

No.	Material	Size, in.	Absolute density, lb./cu. ft.	Maximum spoutable bed depth, in.	Minimum air flow for spouting, F.P.S. superficial
1	Brucite	0.0232	156.5	27.5	0.56
2	Coffee beans	0.3×0.45	39.5	20.0	3.22
3	Lima beans	0.5×0.75	83.0	11.4	4.43
4	Mustard seeds	0.0855	75.7	34.0	2.57
5	Rape seeds	0.0691	68.9	30.0	2.01
6	Sunflower seeds	0.315×0.473	....	15.0	3.06
7	Oats	0.118×0.394	....	19.0	2.42
8	Wheat	0.125×0.25	85.9	30.0	3.53
9	Peas	0.25	86.6	12.0	5.31
10	Ottawa sand (−20+35)	0.0232	145.0	27.0	0.75
11	Shale (−14+20)	0.0390	128.8	36.0	1.21
12	Gravel (−4+8)	0.139	166.6	25.0	4.31
13	Gravel (−8+14)	0.0695	164.0	46.0	3.27

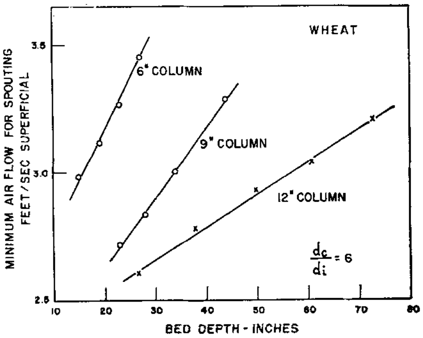

Fig. 17. Effect of Bed Depth on Minimum Air Flow Required for Spouting.

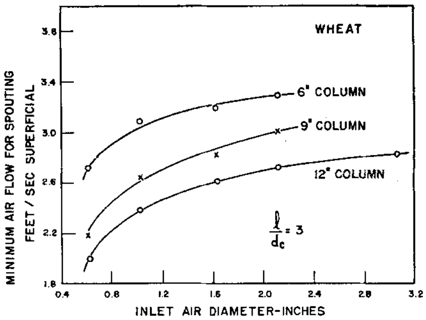

Fig. 18. Effect of Air Inlet Diameter on Minimum Air Flow Required for Spouting.

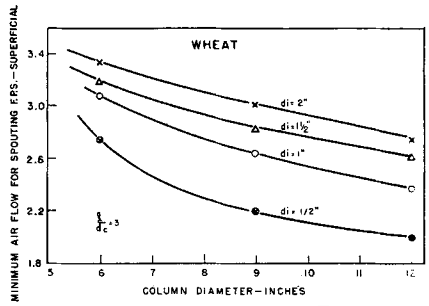

Fig. 19. Effect of Column Diameter on Minimum Air Flow Required for Spouting (Varying Air Inlet Diameter).

The value of the preceding expression for each 2-in. increment of the spout has been worked out by use of v_p from Figure 13 and v_a from Figure 11. This value, on substitution in Equation (1), gives the pressure drop per foot due to the solids density in the spout from which the voidage in the spout has been calculated. The results are included in Figure 14 and check fairly well with the voidage obtained from the solids flow in the annulus.

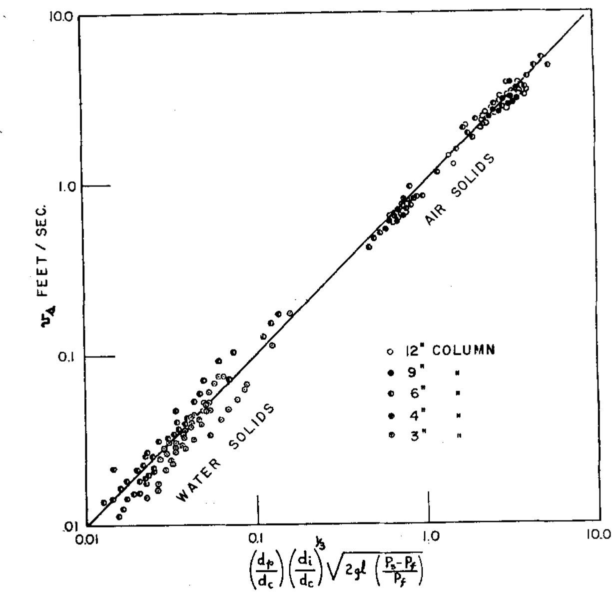

Fig. 20. Correlation of Data on Minimum Fluid Flow Required for Spouting.

EFFECT OF MAJOR VARIABLES ON SPOUTING BEHAVIOR

The effect of such variables as column design and physical properties of the solids and the fluid on spouting behavior has been investigated.

Experimental

To study the effect of column design, wheat was chosen as a typical solid material, and air was used as the spouting medium. The experimental work was conducted in 4-, 6-, 9-, and 12-in.-diam. columns. The 4- and 6-in. columns were made of glass with metal cones; the two larger columns were of sheet iron. In each case an 85° cone was used at the base of the column. Data were taken on the maximum spoutable bed depth and the air requirement for spouting by use of varying air-inlet sizes for each of the foregoing columns. Some preliminary work has been conducted in a 2-ft.-diam. Plexiglas column.

For investigating the effect of the physical properties of solids on spouting behavior, a 6-in.-diam. glass column with a 3/8-in. standard pipe for air inlet at the base of an 85° (included) angle cone was used. A variety of solid materials of different sizes, densities, shapes and, surface characteristics were studied, air being used as the spouting fluid.

The major part of the work was done on air-solids spouting; however, to obtain an idea of the variation of fluid density on the flow required for spouting, experiments were also conducted with water as the spouting medium. Data were taken on 3-, 4-, and 6-in.-diam. glass columns using different water inlet sizes (1/16 to 1/2 in.) for a variety of solid materials. With water the circulation of solids has some resemblance to that in a "teeter"(*8*).

Results and Discussion

Maximum Spoutable Bed Depth. The maximum bed depth which can be made to spout has been found to depend upon the air-inlet diameter, the column diameter, and the physical properties of the solids.

Data on maximum spoutable bed depth as a function of air-inlet diameter for the 4-, 6-, 9-, and 12-in.-diam. columns, reported in Figure 15, indicate that deeper beds can be spouted with smaller air-inlet size. The curves, however, tend to flatten out for higher values of d_i until a sharp break occurs. This break represents the point at which the air-inlet diameter has become too large to cause a spout; at this point the bed would tend to fluidize. No experimental observations have been made in this region for wheat, and the dotted lines merely indicate the expected behavior.

The effect of column diameter on bed depth is clearly brought out by the series of curves in Figure 16, which shows λ_{max} against d_c for different ratios of d_c/d_i. Larger diameter columns permit higher spoutable bed depths; for example, in the 6-in. column the spoutable bed depth is limited to 26 in., and a bed as deep as 95 in. can be spouted in the 12-in.-diam. column.

Data on the maximum spoutable bed depths for a variety of solids in the 6-in.-diam. column is reported in Table 1. The factors governing the maximum spoutable bed depth are complex and possibly include the interparticle friction of the solids besides their size, shape, and density. A correlation of the data on maximum spoutable bed depth was not found possible at this stage.

Air Flow Required for Spouting. The minimum air flow required for spouting has been studied as a function of bed depth, column diameter, air-inlet diameter, and physical properties of the solids. Data were taken with the wheat-air system to establish the effect of bed depth, column diameter, and air-inlet diameter, and the resultant significant trends are presented in Figures 17 to 19.

Minimum air required for spouting is plotted against bed depth in Figure 17 for the 6-, 9-, and 12-in.-diam. columns. The curves indicate that the air flow for spouting increases with bed depth, in contrast with the results in a fluidized bed, where the air flow is relatively independent of bed depth. The effect of column diameter on air flow for spouting is shown in Figure 19, which gives the superficial air velocity required for spouting as a function of column diameter. The series of curves in Figure 19 is for different values of air-inlet diameters and for a fixed λ/d_c ratio, indicating that lower superficial velocities are necessary for spouting in larger diameter columns. The air required for spouting increases with air-inlet diameter, as is indicated by Figure 18, which shows data plotted for the 6-, 9-, and 12-in. columns for an λ/d_c ratio of 3. The curve for the 12-in.-diam. column indicates that a sixfold increase in the air-inlet size caused an increase of about 35% in the air requirement.

The data plotted in the foregoing figures were obtained using 85° (included) angle cones for all the columns. Preliminary work on the 24-in.-diam. column by use of a 45° cone indicates that spouting is much more stable, and the air flow required for spouting is considerably lower with the steeper cone. For a 60-in.-deep bed of wheat in the 24-in. column, the air requirement was about 25% lower with a 45° cone than with an 85° cone. In the 6-in. column, however, the cone angle (85°, 60°, and 45°) did not show any marked influence on either the spouting behavior or the minimum air flow required for spouting. Further work is being conducted to establish the effect of cone angle on spouting behavior in different-sized columns.

TABLE 2.—DATA ON MINIMUM AIR REQUIREMENT FOR SPOUTING OF VARIOUS MATERIALS, 6-IN.-DIAM. COLUMN, ⅜-IN.-DIAM. AIR INLET

		Physical properties			
No.	Material	Effective particle diam., in.	Absolute density, lb./cu. ft.	Bed depth, in.	Air flow, ft./sec. superficial
1	Peas	0.2500	86.6	12 10 8	5.33 4.76 4.15
2	Wheat	0.1250	85.9	30 24 18 12	3.52 3.21 2.88 2.44
3	Mustard seeds	0.0855	75.2	30 24 18 12	2.54 2.19 1.82 1.44
4	Rape seeds	0.0691	68.9	30 24 18 12	2.02 1.72 1.44 1.15
5	Ottawa sand (−20+35 mesh)	0.0232	145	24 20 16 12	0.74 0.68 0.61 0.55
6	Gravel (−4+8 mesh)	0.1390	166.6	24.5	4.67
7	Gravel (−8+14 mesh)	0.0695	164.0	35.6	3.18
8	Gravel (−14+20 mesh)	0.0394	160.0	48.5	1.72
9	Gravel (−4+8) 1 (−8+14) 1	0.1320	165.3	31.7	3.14
10	Gravel (−8+14) 1 (−14+20) 1	0.0463	162.0	42.4	2.04
11	Gravel (−14+20) 1 (−20+35) 1	0.0240	158.0	26.5	0.82
12	Wheat 1 Mustard 1	0.0977	80.8	27.7	2.60
13	Wheat 1 Mustard 1 Peas 1	0.0997	82.7	22.3	2.91

TABLE 3.—SOLID MATERIALS USED WITH WATER AS THE SPOUTING MEDIUM

		Particle size		
No.	Material	Tyler mesh	d_p, in.	Absolute density, lb./cu. ft.
1	Quartz (crushed)	20/35	0.0232	164
2	Quartz (crushed)	14/20	0.0394	164
3	Catalyst (spheres)	6/8	0.124	219
4	Catalyst (spheres)	4/6	0.1504	219
5	Alundum	10/14	0.0555	242
6	Ottawa sand	20/35	0.0232	145
7	Gravel	8/14	0.0695	164
8	Gravel	14/20	0.0394	160
9	Gravel	20/35	0.0232	159
10	Galena	20/35	0.0232	464
11	Brucite	8/14	0.0695	156.5
12	Brucite	14/20	0.0394	156.5

Data on minimum air requirement for a variety of solid materials are given in Table 1. The air requirement was determined as a function of bed depth also for relatively spherical particles; the results are tabulated in Table 2, which also includes the air-requirement data at single bed depth for three sizes of gravel and a number of mixtures.

The solid materials used with water as the spouting medium are listed in Table 3, which also gives the physical properties. The results of this investigation are reported in Table 4.* The effect of the solids-particle size and density and of fluid density on fluid requirement for spouting has been established in the form of a dimensionless correlation. The correlation also includes bed depth, air-inlet diameter, and column diameter;

*Table 4 may be obtained from the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., as document 4562 for $1.25 for microfilm or photoprints.

the individual effect of these on air flow requirement has already been discussed.

$$v_s = \left(\frac{d_p}{d_c}\right)\left(\frac{d_i}{d_c}\right)^{1/3}\sqrt{\frac{2g.\lambda.(\rho_s - \rho_f)}{\rho_f}}$$

The correlation has been derived empirically on the basis of the data in Tables 2 and 4*; however, the groups used may have theoretical significance. The plot of the data, based on the foot, pound, second system of units, is shown in Figure 20 for the following range of variables:

d_p = 0.023-0.25 in.
d_i = 1/16-2 1/8 in.
ρ_s = 69-464 lb./cu.ft.
d_c = 3-12 in.
λ = 3 1/2-106 in.
ρ_f = 0.073 and 62.4 lb./cu.ft.

For wheat, the smaller diameter was taken as the particle size since in the spout the particles would have a tendency to align themselves so as to offer a maximum resistance to the frictional drag of the air. This would be achieved when the smaller diameter of the wheat particle was normal to the flow of air. Visual observations in the spout justify this assumed orientation. The particle diameter used in the correlation for other materials is equivalent to the average screen opening, as these particles are essentially isometric in shape. For mixtures, the arithmetic average diameter and an average value of density weighted according to the mass fraction has been used.

APPLICATION TO WHEAT DRYING

The spouting-bed technique provides good contacting of gases with coarse solid particles in a cycling bed and should therefore be applicable to continuous drying. Wheat was used as the material tested.

A small pilot plant was built consisting of a 12-in.-diam. dryer column and a 9-in.-diam. cooler column each about 6 ft. high, connected by a series of overflow pipes so that different bed depths might be studied. Steam was used to preheat the air to the dryer, into which wheat of a known moisture content was fed at a predetermined rate. From here it overflowed into the cooler, average retention time being dependent on feed rate and bed volume.

The variables studied included inlet-air temperature (210° to 350°F.), initial moisture content of wheat (16 to 26%, wet basis), feed rate (240 to 600 lb./hr.), and bed depth (12 to 48 in.). The highest inlet-air temperature used without causing damage to the wheat was 350°F., which resulted in a bed temperature of 118°F. Under these conditions 600 lb./hr. of wheat were dried through a moisture range of 4%.

The cycling motion of the bed, coupled with the continuous mixing of fresh feed with the bed wheat, resulted in quite low (100° to 118°F.) bed temperatures despite the high inlet-air temperatures. A substantial amount of the sensible heat of the wheat entering the cooler was available for further moisture removal. Over-all heat efficiencies of 65% were obtained.

The drying behavior of the wheat indicated that this method should be particularly applicable to the drying of thermally sensitive coarse particles.

COMPARISON WITH OTHER TECHNIQUES

Spouting appears not to be just a special form of fluidizing. It can be applied to materials that are either too coarse or of too uniform a particle size for good fluidization. In fluidizing there is a net vertical upward motion of particles in the center of the bed and a net downward motion of particles at the wall, but the local effect is one of an apparently random motion of fine solid particles, with the entire bed expanded. In spouting, the upward motion is very rapid and is restricted to a well-defined central core. In the remainder of the bed there is never any upward motion of particles; rather, a packed bed is moving steadily downward and, to some extent, inward. This steady motion eliminates back mixing(*3, 9*). At the same time the fairly rapid bed turnover tends to eliminate the temperature differences usually associated with conventional packed-bed systems.

Studies on heat and mass transfer in a spouted bed are being conducted in order to compare the effectiveness of the technique with packed- and fluidized-bed systems.

SUMMARY

A study was made of the contacting of coarse solid particles and gases in a bed in which the gases forced the solids to cycle in a regular fashion. The flow pattern of both the gas and solids has been described, and the effect of column design and physical properties of solids and fluids on the flow rates required to produce spouting have been correlated.

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NOTATION

A = cross-sectional area of spout, sq. ft.
d_c = column diameter
d_i = fluid-inlet diameter
d_p = particle diameter
dP_f = change in static pressure due to friction
dP_a = change in static pressure due to acceleration
dP_w = change in static pressure due to solids density
g = acceleration due to gravity
h = spout level
λ = bed depth, in.
λ_{max} = maximum spoutable bed depth, in.
m = solids flow, lb./sec.
v_p = particle velocity in spout, ft./sec.
v_s = minimum superficial fluid velocity for spouting, ft./sec.
v_a = superficial air velocity through spout, ft./sec.
ρ_s = absolute density of solids, lb./cu.ft.
ρ_f = fluid density, lb./cu.ft.
ρ_b = density of solids in spout, lb./cu.ft.
ΔP = static pressure drop, in. of water

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* See footnote on page 163.