# POWDERS, HANDLING, BULK POWDERS

Work on the development of the theory of bulk solids flow began in the early 1950s. Until that time, there had not been a recorded organized scientific approach to the analysis and design of devices to store and discharge bulk solids. Design of bins, hoppers, and feeders for powder flow was based on experiment and previous experience. Bulk solids were thought to behave much like liquids, and thus were expected to flow easily from bins. Powder flow is not always reliable, however, and attempts to approach the field of bulk solids flow using the techniques of fluid mechanics (qv) were not successful.

During the late 1950s and early 1960s Jenike employed a soil mechanics continuum approach to powder handling, developing a logical, theoretical basis to bulk solids flow (1). Testing equipment and methods were developed along with design techniques. The basic concepts of bulk solids flow have since been expanded to allow design of bins, hoppers, and feeders (2–5).

## 1. Definitions

The following definitions are particular to bulk powders handling.

| | |
|---|---|
| Bin or silo | container for bulk solids having one or more outlets for withdrawal of solids either by gravity alone or by flow-promoting devices which assist gravity |
| Bulk solid | material consisting of discrete solid particles, which are submicrometer to several centimeters in size, handled in bulk form, as opposed to unit handling |
| Cylinder | vertical part of a bin (constant cross-sectional area) |
| Discharger | device used to enhance material flow from a bin but which is not capable of controlling the rate of withdrawal |
| Feeder | device for controlling the rate of withdrawal of bulk solid from a bin |
| Flow channel | space in a bin through which a bulk solid is actually flowing during withdrawal |
| Hopper | converging part of a bin (changing cross-sectional area) |

## 2. Flow Problems

Bulk solids do not always discharge reliably. Unreliable flow, which can occur with some frequency, can be expensive in terms of inefficient processes, wasted product, and operational complications. Predictable flow is often impeded by the formation of an arch or rathole, or fine powders may flood uncontrollably.

Solids flow problems can occur individually or in combination. Five common flow problems, which occur when handling bulk solids follow.

*2.0.0.1. No-Flow.* The problem of no flow may occur when an attempt is made to initiate flow such as by opening a gate or starting a feeder. One of two things may happen. In the first, an arch (bridge, dome) forms

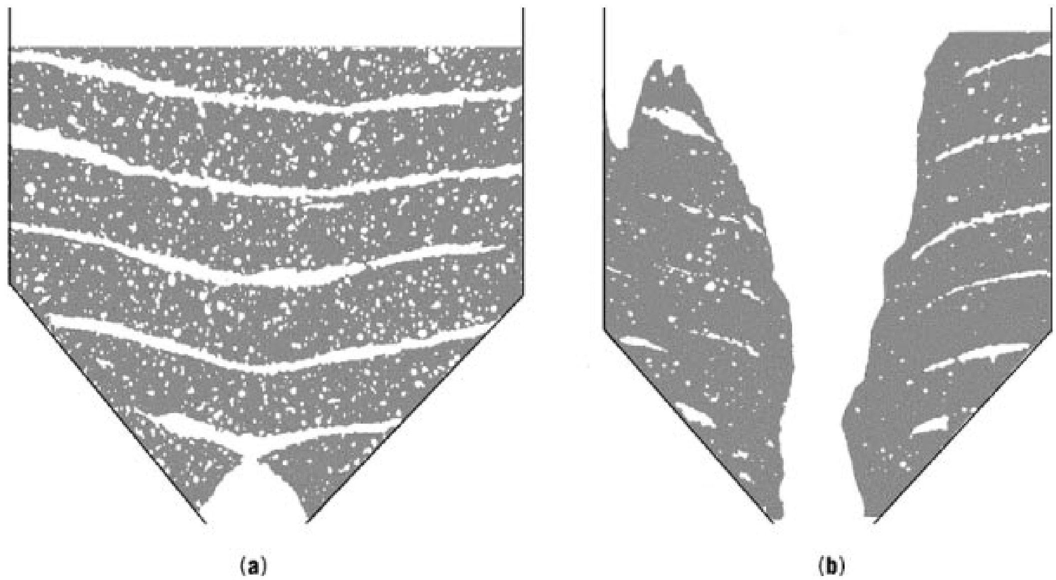

**Fig. 1.** Examples of no-flow situations where the darkened areas represent material within the bin: (**a**) cohesive arch at the outlet of a bin, and (**b**) stable rathole formed within bin.

over the outlet (Fig. 1**a**). Sometimes the only way to initiate flow is to use force greater than that of gravity to overcome the arch and force material flow. Devices such as sledge hammers, vibrators, and/or air blasters are commonly used. The second form of a no-flow problem is commonly referred to as a stable rathole (pipe, core) (Fig. 1**b**). In this case, some material discharges as the feeder or gate is operated. However, because of a material's cohesive strength, as the flow channel empties out, the resulting hole becomes stable, and material stops flowing. Extreme measures are often required to reinstate flow.

*2.0.0.2. Erratic Flow.* A combination of the two no-flow conditions can lead to erratic flow. If flow has been initiated but a stable rathole develops, then when the rathole collapses using vibration, the material may arch as it impacts the outlet. Flow may be restarted by vibration and maintained for a short time until the rathole forms again. Erratic flow can be a serious problem when handling bulk solids owing to fluctuating flow rates and bulk densities, and unreliable discharge. It can also jeopardize the structural integrity of the bin when a rathole collapses.

*2.0.0.3. Flooding.* When a stable rathole forms in a bin and fresh material is added, or when material falls into the channel from above, a flood can occur if the bulk solid is a fine powder. As the powder falls into the channel, it becomes entrained in the air in the channel and becomes fluidized (aerated). When this fluidized material reaches the outlet, it is likely to flood from the bin, because most feeders are designed to handle solids, not fluids (see Fluidization).

*2.0.0.4. Limited Discharge Rate.* Bulk solids, especially fine powders, sometimes flow at a rate lower than required for a process. This flow rate limitation is often a function of the material's air or gas permeability. Simply increasing the speed of the feeder does not solve the problem. There is a limit to how fast material flows through a certain sized opening. For fine powders the limit is strongly influenced by the counterflow of gas through the outlet.

*2.0.0.5. Segregation.* The problem of segregation occurs when a bulk solid composed of different particle sizes or densities separates. The result can be quite serious if uniform density or mixed material is required for a process.

## 3. Flow Patterns

### 3.1. Funnel Flow

A funnel flow pattern occurs when some of the material in a bin or hopper moves toward the outlet while the rest remains stationary. This happens when the walls of the hopper section at the bottom of the bin are not sufficiently steep or smooth to cause the material to flow along them. In other words, the friction which develops between the hopper and material is great enough to inhibit flow at the interface. As a result, the material flows only in a narrow channel, usually directly over the outlet. The size of the flow channel approximates the largest dimension of the outlet. It is equal to the diameter of a circular outlet or the diagonal of a square or rectangular outlet. Using relatively free-flowing materials, the funnel flow channel may expand to the vertical walls of the bin if the bin is tall enough.

A funnel flow bin typically exhibits a first-in/last-out type of flow sequence. If the material has sufficient cohesive strength, it may bridge over the outlet. Also, if the narrow flow channel empties out, a stable rathole may form. This stable rathole decreases the bin's live or usable capacity, causes materials to cake or spoil, and/or enhances segregation problems. Collapsing ratholes may impose loads on the structure that it was not designed to withstand.

For fine powders, funnel flow bins often exhibit high discharge rates, thus controlling flow rate is always a challenge. A funnel flow channel is often unstable. The actual size and shape of the stagnant region is neither well defined nor constant. This channel can change its size radically or collapse, creating flow rates that range from no-flow conditions to complete flooding, also affecting the bulk density at the outlet.

Funnel flow bins are only suitable for bulk solids that are coarse, free flowing, and do not degrade, and for use when segregation is not important. For such materials, the principal benefits of funnel flow bins are reduced headroom and lower initial cost for the bin (excluding feeders or dischargers). Examples of funnel flow bins are shown in Figure 2.

### 3.2. Mass Flow

A material is considered to flow in mass flow when all of it is in motion whenever any is withdrawn. This means that material flows along the walls. The walls of the hopper section are thus required to be steep and smooth (Fig. 3). As long as the outlet is large enough to prevent arching, all the material starts to move as discharge begins keeping the contents of the bin fully live. Stable ratholes cannot form.

Because of the first-in/first-out sequence of flow, mass flow bins can usually handle bulk solids that are cohesive or degrade with time. The bin's smooth, steep hopper section promotes uniform flow, preventing stagnation. A material's discharge bulk density is almost independent of the head of material in the bin. Segregation of particles is minimized as the fines and coarse particles are reunited at the outlet. In some instances, mass flow bins having special velocity profiles are used for in-bin blending. One possible disadvantage of mass flow bins is the headroom required for the steep hopper section.

Fine powders are easily handled in a mass flow bin where the flow channel is stable and predictable. However, the maximum flow rate of a fine powder through the outlet of a mass flow bin is low compared to that of a coarse, granular solid. For fine materials, the expansion and contraction of voids during flow can create an upward air pressure gradient at the outlet of a mass flow bin. During discharge, this upward gradient acts against gravity, reducing the discharge rate. Such gradients do not usually form with coarser particle materials. The latter are more permeable and thus allow air to flow freely into and out of the voids as they expand and contract.

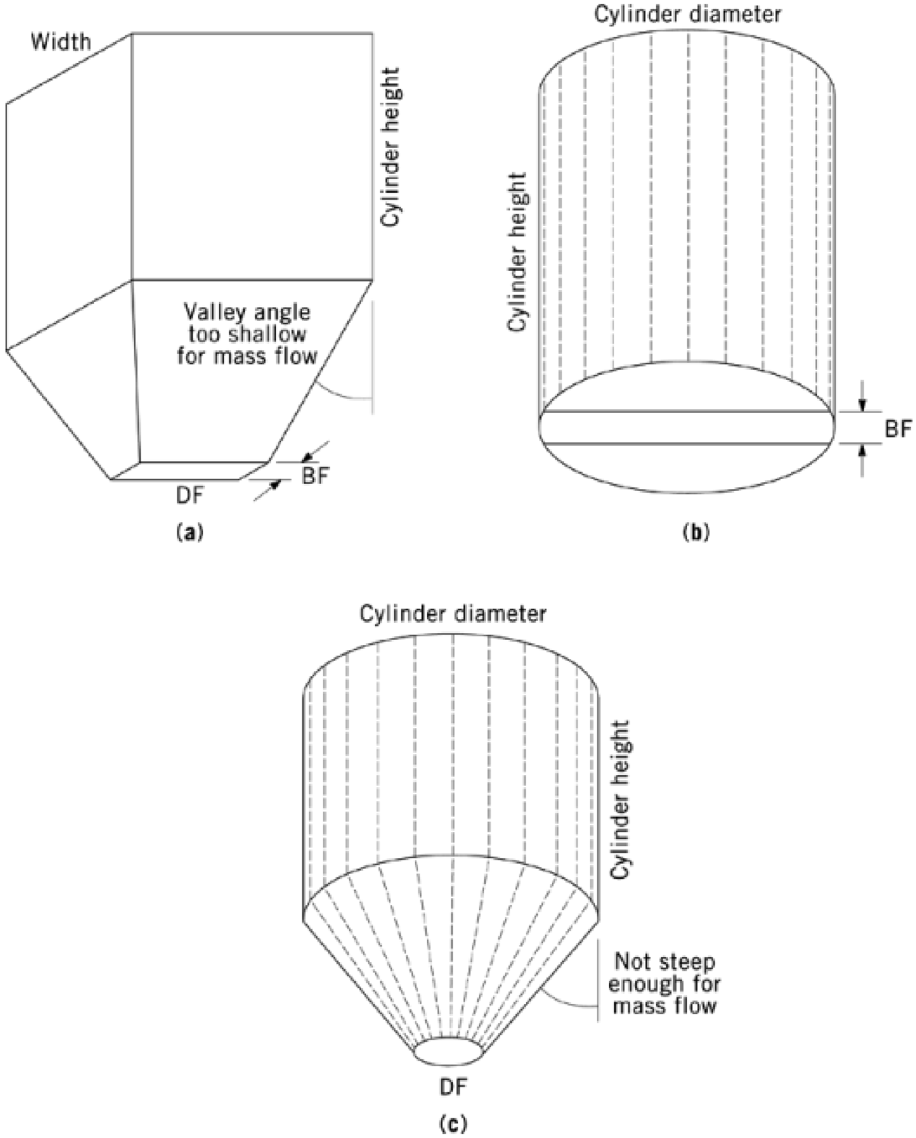


**Fig. 2.** Examples of funnel flow bins where BF is the outlet width and DF is the outlet diameter or length: (**a**) pyramidal hopper; (**b**) flat bottom; and (**c**) conical hopper.

#### 3.3. Expanded Flow

Expanded flow uses the best aspects of funnel flow and mass flow by attaching a mass flow hopper section below one that exhibits funnel flow. The flow pattern expands sufficiently at the top of the mass flow hopper to prevent a stable rathole from forming in the funnel flow hopper above it. In this way, the flow channel is expanded, material flow is uniform, and the bin height is limited.

Expanded flow bins, shown in Figure 4, are recommended for storing large quantities of nondegrading solids. This design is sometimes useful when modifying existing funnel flow bins. An expanded flow bin should

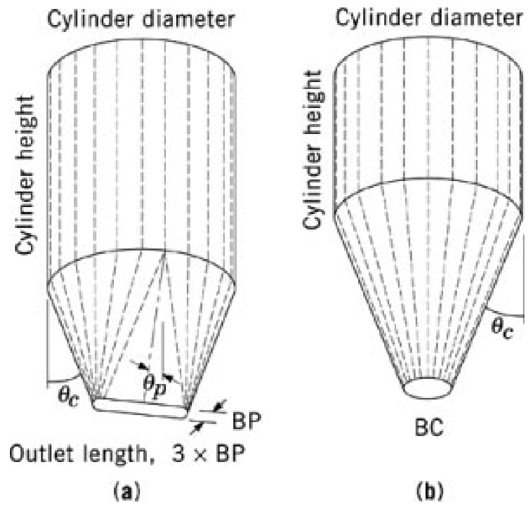


**Fig. 3.** Examples of mass flow bins: (**a**) transition hopper, where $\theta_c$ is the conical end-wall angle, $\theta_p$ is the side-wall angle, and BP is the outlet width; (**b**) conical hopper, where $\theta_c$ is the hopper angle and BC is the outlet diameter.

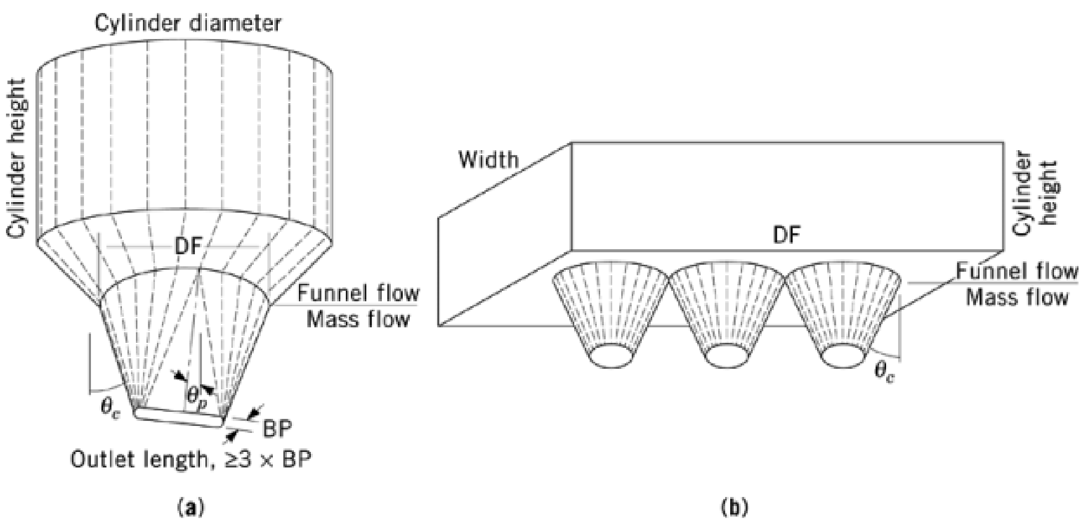


**Fig. 4.** Examples of expanded flow bins showing where funnel flow becomes mass flow: (**a**) funnel flow cone modified with mass flow transition hopper, where BP=outlet width, DF=diameter, $\theta_c$=end−wall angle, and $\theta_p$=side−wall angle; (**b**) long funnel flow slot modified with mass flow cones, where DF=slot length and $\theta_c$=hopper angle.

be considered for applications that require bin diameters greater than ca 6 m. Bins of smaller diameter should usually be designed for full mass flow, if flow along the walls is required.

## 4. Measurement of Flow Properties

In order to develop the proper flow pattern, knowledge of a material's flow properties is essential. Standard test equipment and procedures for evaluating solids flow properties are available (6). Direct shear tests, run to

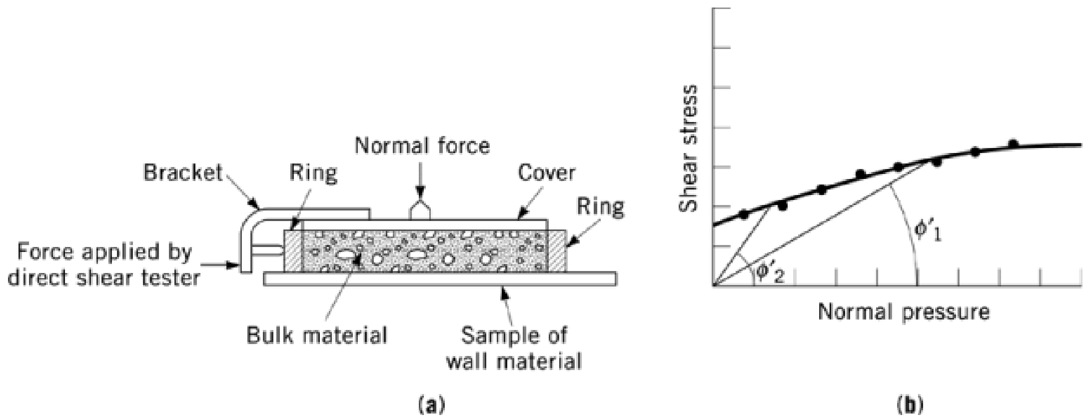


**Fig. 5.** Wall friction test: (**a**) apparatus for measurement, and (**b**) results, where $\varphi'$ is the wall friction angle.

measure a material's friction and cohesive properties, allow determination of hopper wall angles for mass flow and the opening size required to prevent arching. Other devices available to evaluate solids flowability include biaxial and rotary shear testers.

#### 4.1. Wall Friction Angles

Wall friction values, important when characterizing the flow properties of a bulk solid, are expressed as the wall friction angle or coefficient of sliding friction. The lower the friction, the less steep the hopper walls need to be to achieve mass flow.

Wall friction values can be measured by sliding a sample of material across a stationary wall surface. This test is performed by placing a retaining ring, as shown in Figure 5**a,** on a flat piece of wall material. Then, using weights and a cover, forces are applied to the material in a direction perpendicular to the wall surface. Material in the ring is forced to slide along the stationary wall material. The resulting shear force is measured as a function of the applied normal force.

Figure 5**b** shows the results of a typical wall friction test. The wall friction angle, designated as $\varphi'$, is defined as the angle formed by a line drawn from the origin to a point on the shear stress–normal pressure curve. The point is selected based on the pressue level at which the angle is to be determined. As the location in a hopper changes, so does the pressure acting on the hopper walls. The tangent of the wall friction angle is the coefficient of sliding friction. For a given bulk material and wall surface, wall friction angle is not necessarily a constant but often varies with normal pressure, usually decreasing as normal pressure increases. Once the wall friction angles have been determined, hopper angles for mass flow can be chosen.

The following variables can affect wall friction values of a bulk solid. (*1*) Pressure: as the pressure acting normal to the wall increases, the coefficient of sliding friction often decreases. (*2*) Moisture content: as moisture increases, many bulk solids become more frictional. (*3*) Particle size and shape: typically, fine materials are somewhat more frictional than coarse materials. Angular particles tend to dig into a wall surface, thereby creating more friction. (*4*) Temperature: for many materials, higher temperatures cause particles to become more frictional. (*5*) Time of storage at rest: if allowed to remain in contact with a wall surface, many solids experience an increase in friction between the particles and the wall surface. (*6*) Wall surface: smoother wall surfaces are typically less frictional. Corrosion of the surface obviously can affect the ability of the material to slide on it.

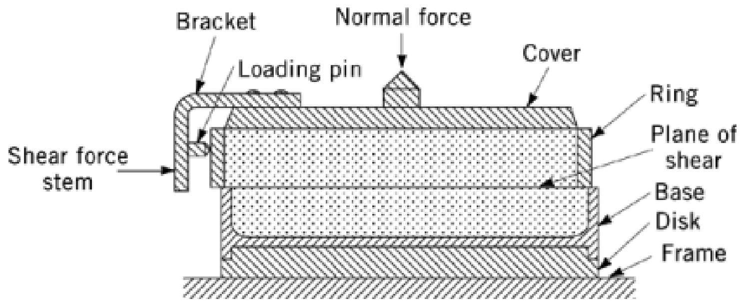


**Fig. 6.** Test apparatus for measurement of cohesive strength.

### 4.2. Flow Function

Another important consideration in bin design is the opening size required to prevent formation of arches and ratholes. A flow obstruction can occur in a bin caused by cohesive arching. Particles can bond together physically, chemically, or electrically. This tendency to bond is termed a material's cohesive strength. Many bulk solids flow like a liquid when poured from a bag. Under these conditions, the material has no cohesive strength. However, when squeezed in the palm of a hand, the material may gain enough cohesive strength to retain the shape of the palm once the hand is opened.

In order to characterize this bonding tendency, the flow function of a material must be determined. Data on flow function can be generated in a testing laboratory by measuring the cohesive strength of the bulk solid as a function of consolidation pressure applied to it. Such strength is directly related to the ability of the material to form arches and ratholes in bins and hoppers.

A material's flow function is usually measured on the same tester as the wall friction angle, although the cell arrangement is somewhat different (Fig. 6). Consolidation values are easily controlled, and the cohesive strength of the bulk solid is determined by measuring interparticle shear stresses while some predetermined normal pressure is being applied.

The cohesiveness of a bulk solid is often a function of the following variables. (*1*) Moisture: typically, cohesiveness rises as moisture content increases. Hygroscopic materials can experience significant increases in moisture when exposed to humid air. (*2*) Particle size and shape: there is no direct correlation between particle size, shape, and cohesiveness. Even so, in most cases, as a bulk solid becomes finer, it also becomes more cohesive and difficult to handle. (*3*) Temperature: a bulk solid's temperature can affect its cohesiveness. For example, many chemicals and plastic powders become more difficult to handle as the temperature rises. Some materials have more strength at constant temperature; others gain cohesive strength as the temperature changes during heating or cooling. (*4*) Time of storage at rest: when a solid resides in a bin or hopper for a period without moving, it can become more cohesive and difficult to handle. (*5*) Chemical additives: in some cases, a small amount of a chemical additive such as fumed silica can cause a cohesive solid to flow more easily.

### 4.3. Compressibility

The bulk density of a solid is an essential value used in the analysis of its flow properties, such as when calculating mass flow hopper angles, opening sizes, bin loads, etc. Loose and/or packed density values are not sufficient. Bulk solids exhibit a range of densities that vary as a function of consolidating pressure. This range of densities, called the compressibility of the solid, can often be expressed on a log–log plot as a line or relationship.

The following variables can affect a material's bulk density. (*1*) Moisture: higher moisture content often makes a material more compressible. (*2*) Particle size and shape: often, the finer the bulk solid, the more compressible it is. The shape of the particles can affect how they fit together and their tendency to break while being compacted. (*3*) Temperature: some materials become more compressible as their temperature increases. This could be due, for example, to softening of the particles. (*4*) Particle elasticity: elastic materials tend to deform significantly when they are compressed.

### 4.4. Permeability

Two-phase (gas–solids) interactions can be analyzed by considering how gas flows through a bed of powder in the presence of a pressure differential across the bed. When flow through the bed is laminar, Darcy's law, which can be used to relate gas velocities to gas pressure gradients within or across the bed, can be written as in equation 1, where $K$ = permeability factor of the bulk solid; $u$ = superficial relative gas velocity through the bed of solids; $\gamma$ = bulk density of the solid in the bed; and $dp/dx$ = gas pressure gradient acting at the point in the bed of solids where the velocity is being calculated.

$$u = -K\left(\frac{dp/dx}{\gamma}\right) \qquad (1)$$

The permeability factor, $K$, has units of velocity and is inversely proportional to the viscosity of the gas. A permeability test is run by passing air through a representative column of solids. The pressure across the bed is regulated, and the rate at which the gas flows is measured. This approach allows the permeability of the bulk solid to be determined as a function of its bulk density. Typically a linear log–log plot results.

Because mass flow bins have stable flow patterns that mimic the shape of the bin, permeability values can be used to calculate critical, steady-state discharge rates from mass flow hoppers. Permeability values can also be used to calculate the time required for fine powders to settle in bins and silos. In general, permeability is affected by particle size and shape, ie, permeability decreases as particle size decreases and the better the fit between individual particles, the lower the permeability; moisture content, ie, as moisture content increases, many materials tend to agglomerate which increases permeability; and temperature, ie, because the permeability factor, $K$, is inversely proportional to the viscosity of the air or gas in the void spaces, heating causes the gas to become more viscous, making the solid less permeable.

## 5. Equipment Design

### 5.1. Hopper Angles for Mass Flow

The wall friction angle for a given bulk material/wall surface combination can be calculated from the results of a wall friction test. This angle, the tangent of which is the coefficient of sliding friction, often varies with the pressure acting normal to the wall surface. From this angle the hopper angles compatible with mass flow can be determined. This is most easily done for hoppers which are either conical or wedge-shaped. There is no magic angle, because mass flow is dependent on both the smoothness and steepness of the hopper wall and the properties of the bulk material involved.

#### *5.1.1. Conical Hoppers*

Design charts for conical hoppers typically are plots of wall friction angles, $\varphi'$, vs hopper angle, $\theta_c$. Charts such as that in Figure 7**a** may be used in several ways. For example, if a 20° from vertical (70° from horizontal) corroded carbon steel hopper is experiencing ratholing, indicative of a funnel flow pattern, and a smooth stainless steel liner to convert the flow pattern to mass flow is suggested, rather than taking a try-it-and-see approach, a wall friction test is run. If the resulting wall friction angle is 15°, this angle combined with the 20°

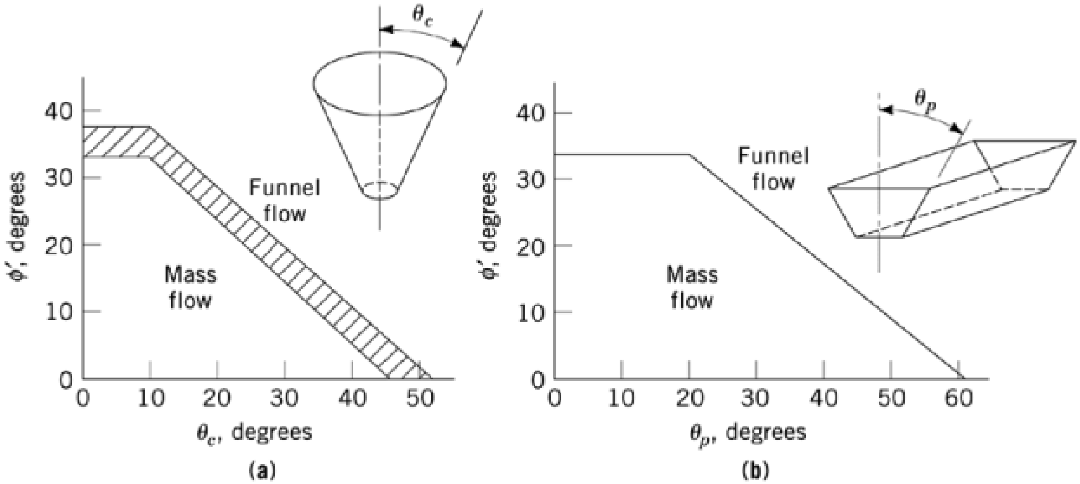


**Fig. 7.** Design chart to determine mass flow for hopper wall angles for (**a**) conical design, where the ▨ area designates uncertainty and (**b**) wedge design. See Figures 3 and 5 for definitions of $\theta_c$, $\theta_p$, and $\varphi'$.

hopper angle is within the mass flow region of the design chart. The stainless liner should be acceptable. If, on the other hand, the wall friction angle on the proposed liner were 30°, the funnel flow pattern would remain.

Another way to use the chart in Figure 7**a** is during the design of a new hopper. The goal is often to determine the least steep hopper angle that allows mass flow for a certain wall material. A wall friction test using the proposed material of construction and actual bulk material can be run. Then, using the measured value of the wall friction angle, the corresponding mass flow region and the appropriate hopper angle can be determined. The edge of the mass flow region yields the shallowest recommended angle for mass flow for this application.

There is an uncertain region which lies between funnel flow and mass flow. Whereas the flow pattern within this region should theoretically be mass flow, slight differences in material properties or hopper angle can result in funnel flow. In effect, this region represents a margin of safety to prevent using a design too close to the funnel flow line. A switch back and forth between mass flow and funnel flow can cause bin vibrations and other problems.

#### *5.1.2. Wedge Hoppers*

Different design charts are used for wedge hoppers (Fig. 7**b**) than for conical hoppers. Values of hopper angle $\theta_p$ (measured from vertical) appear on the horizontal axis; wall friction angles $\varphi'$ are on the vertical axis. There is no uncertain region in this chart as on the conical hopper design chart, because there is no sharp boundary line between mass flow and funnel flow in wedge-shaped hoppers. In fact, mass flow can at times occur to the right of the design line, in the region labeled funnel flow. Thus, a wedge geometry is more forgiving than a conical one and therefore more capable of handling materials having a wider range of flowability.

Wedge hopper design charts are used in the same way as the conical design charts. If $\varphi'$ is 15°, the resulting maximum wedge hopper angle for mass flow is 40° from vertical. This is 12° less steep than the required conical hopper angle. Mass flow wedge-shaped configurations require significantly less headroom than conical hoppers. The side walls of transition- and chisel-shaped hoppers can be designed based on $\theta_p$ provided the outlet length-to-width ratio is at least 3:1.

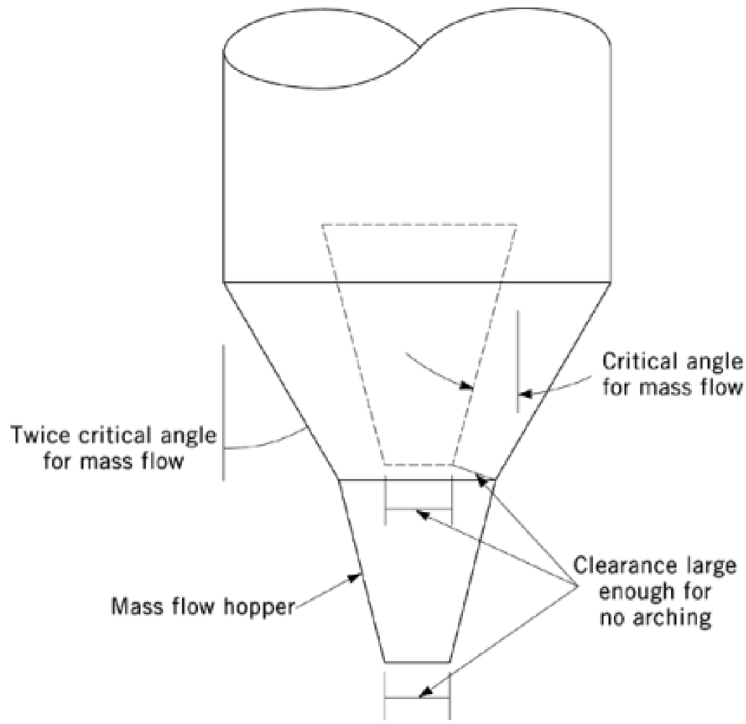


**Fig. 8.** BINSERT system to convert funnel flow to mass flow.

#### *5.1.3. Other Designs*

Mass flow can also be achieved by the use of inserts. One popular type, called a BINSERT (Jenike & Johanson, Inc.), consists of a hopper-within-a-hopper (Fig. 8) (7). Material flows through both hoppers. By choosing appropriate angles and materials of construction, the inner hopper can force flow along the walls of the outer hopper at a less steep angle than would be possible if the inner hopper were not present. By careful choice of the hopper design, a BINSERT can provide in-bin blending or, alternatively, a uniform velocity profile which is excellent in preventing segregation.

### 5.2. Outlet Size Determination

The second consideration for proper design of a mass flow bin is the size of the outlet required to prevent arching and to achieve the required discharge rate.

There are two mechanisms by which arching can occur: particle interlocking and cohesive strength. The minimum outlet size required to prevent mechanical interlocking of particles is directly related to the size of the particles. The diameter of a circular outlet must be at least six to eight times the particle size, and the width of a slotted outlet must be at least three to four times the particle size. These ratios normally only govern the outlet size of mass flow hoppers if the particles are at least 0.6 cm or larger.

If most of the particles are less than ca 0.6 cm in size, flow obstructions can occur by physical, chemical, or electrical bonds between particles. This cohesiveness is characterized by the bulk material's flow function. The forces acting to overcome a cohesive arch and cause flow are described by a hopper's flow factor, which can be obtained from the design charts (see Fig. 7). The minimum opening size required to prevent a cohesive arch from forming can be calculated from the comparison of the flow factor and flow function.

As for the particle interlocking mechanism, the minimum diameter to prevent cohesive arching for a circular outlet is about twice the minimum width of a slotted outlet. For example, if a 30-cm diameter opening is required to prevent arching in a cone, arching in a slotted outlet can be prevented using as little as a 15-cm wide opening. Note that the length of a slotted outlet should be at least three times its width.

Sizing an outlet to achieve the required discharge rate is more difficult but no less important, particularly for fine powders. All bulk materials have a maximum rate at which they discharge through a hopper opening of a given size. For coarse, free-flowing bulk materials, a good approximation of this rate from a mass flow hopper is shown in equation 2, where $Q$ = maximum steady discharge rate, $\gamma$ = bulk density, $A$ = cross − sectional area of outlet, $B$ = outlet diameter or width, $g$ = acceleration owing to gravity, $m = 1$ for circular opening and 0 for slotted opening, and $\theta$ = hopper angle (measured from vertical) in degrees. A modification of this equation takes particle size into account. This modification is only important if the particle size is a significant fraction of the outlet size (8).

$$Q = \gamma A (Bg/2(1+m)\tan\theta)^{1/2} \qquad (2)$$

Usually the rate, $Q$, is far in excess of the required rate, especially if the bulk material consists primarily of coarse particles. Slowing down the discharge rate requires a feeder. Fine powders, on the other hand, have considerably lower maximum discharge rates when exiting from a mass flow bin, because of the interaction between air (or gas) and solid particles as reflected in the permeability of the material.

Sizing the outlet of a funnel flow bin involves consideration of both arching and ratholing. Minimum dimensions to overcome both can be calculated from the material's flow function.

### 5.3. Structural Considerations

Silos, bins, and hoppers fail, in one way or another, each year. The causes of silo failures are many and varied (9). Such failures can range from a complete and dramatic structural collapse, to cracking in a concrete wall, or denting of a steel shell. This last is often a danger signal indicating that corrective measures are required.

#### *5.3.1. Design*

Silo design requires knowledge of the material's flow properties, flow channel geometry, flow and static pressure development, and dynamic effects. Problems like ratholing and vibration have to be prevented, while assuring reliable discharge at the required rate. Nonuniform loads, thermal loads, and the effects of nonstandard fabrication details must be considered. Above all the designer must know when to be cautious in the face of incomplete or misleading information or recommendations that come from handbooks.

The designer must have a full appreciation of load combinations, load paths, primary and secondary effects on structural elements, and the relative flexibility of the elements. Special attention must be given to how the most critical details in the structure are to be constructed so that the full requirements and intent of the design can be realized (10).

Some flow-related loading conditions which many designers fail to anticipate include bending of circular walls caused by eccentric withdrawal; nonsymmetric pressures caused by some types of inserts; and self-induced vibrations.

#### *5.3.2. Construction*

In the construction phase there are two ways problems can arise. The more common of these is poor workmanship. Uneven foundation settlement and faulty construction, eg, use of the wrong materials or insufficient quantity of rebars, are but two examples. Only qualified builders, close inspection during construction, and enforcement of a tightly written specification are necessary factors.

The other cause of construction problems is the introduction of badly chosen, or even unauthorized, changes during construction in order to expedite the work. Any changes in details, material specifications, or erection procedure must be given careful consideration by both the builder and silo designer.

#### *5.3.3. Silo Usage*

If a bulk material other than the one for which the silo was designed is placed in the silo, the flow pattern and loads may be completely different. The load distribution can be radically changed if alterations to the outlet geometry are made, if a side outlet is put in a center discharge silo, or if a flow controlling insert or constriction is added. Some of the problems which can occur include collapse of large voids resulting in immense impact forces; development of mass flow in silos designed structurally for funnel flow; drastic means of flow promotion, eg, use of explosives or air cannons; buckling of an unsupported cylindrical wall below an arch of stored bulk material; metal fatigue caused by externally mounted bin vibrators; and dust explosions.

#### *5.3.4. Maintenance*

There are two types of maintenance work required (11). The first is regular preventative work, such as the periodic inspection and repair of a liner used to promote flow, protect the structure, or both. Loss of a liner may be unavoidable for an abrasive or corrosive product, yet maintaining a liner in proper working condition is necessary if the bin or silo is to operate as designed. The second area of maintenance involves looking for signs of distress, eg, cracks, wall distortion, or tilting of the structure. If evidence of a problem appears, expert help should be summoned immediately. An inappropriate response to a sign that something is going wrong can precipitate a failure even faster than leaving it alone. The common, instinctive response to discharge material so as to lower the fill level is often inappropriate.

Wear owing to corrosion and/or erosion can be particularly dangerous. For example, as carbon steel corrodes, the reduced wall thickness can eventually lead to a structural failure. This problem can be compounded through erosive wear of the silo wall.

## 6. Feeders

Most flow problems can be overcome by using a mass flow design if the mass flow pattern developed by the bin is not disturbed. Thus a properly designed feeder or discharger must be employed. A feeder is used whenever there is a requirement to transfer solids at a controlled rate from the bin to a process or a truck. A discharger is used when there is a need to discharge solids, not control the rate of discharge.

To be consistent with a mass flow pattern in the bin above it, a feeder must be designed to maintain uniform flow across the entire cross-sectional area of the hopper outlet. In addition, the loads applied to a feeder by the bulk solid must be minimized. Accuracy and control over discharge rate are critical as well. Knowledge of the bulk solid's flow properties is essential.

There are several types of feeders available to handle bulk solids, but these can be divided into two categories: volumetric and gravimetric. A volumetric feeder discharges a certain volume of material as a function of time. This type of discharge is adequate for many solids feeding applications. For mass flow designs, feed uniformities in the range of $\pm 2$ to 5% on a minute-to-minute basis are easily achieved using most volumetric designs. A disadvantage of volumetric feeding is that the feeder does not recognize bulk density changes.

A gravimetric feeder relies on weighing the material to achieve the required rate. Feed accuracies of $\pm 1/4\%$ are obtainable using a properly designed gravimetric feeder. A disadvantage of such a feeder is that it is usually more expensive than a volumetric device.

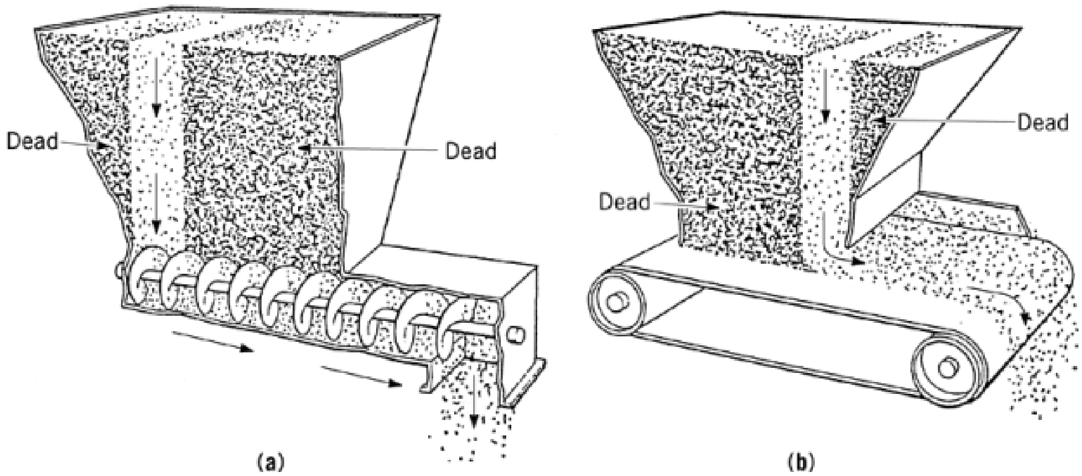


**Fig. 9.** Preferential flow channel caused by (**a**) a constant pitch screw feeder and (**b**) a belt feeder.

#### 6.1. Volumetric Feeders

Examples of volumetric feeders are screws, belts, rotary valves, louvered, and vibratory.

##### *6.1.1. Screw Feeders*

Screws are primarily used when feed over a slotted outlet is required. Screws are a good choice when an enclosed feeder is required, when space is restricted, when handling dusty or toxic materials, or when attrition (particle breakage) is not a problem. A screw is composed of a series of flights that are wound around a common shaft. The flights have a particular diameter and pitch (the distance between flights). Some screws have constant pitch flights; others vary. The screw shaft has to be sized to prevent deflection (12).

Many applications use screws with constant pitch to feed material from a slotted opening. The configuration shown in Figure 9**a** shows a constant pitch and constant diameter causing a preferential flow channel to form at the back (over the first flight) of the screw. This type of flow destroys the mass flow pattern and potentially allows some or all of the problems discussed about funnel flow.

The key to proper feeder design is to allow material to be withdrawn over the entire cross-sectional area of the outlet. In order to ensure this, the capacity of the feed device must increase as material is transferred to the discharge end. Tapering the diameter theoretically increases capacity; however, material is likely to bridge over the narrowed end flights, creating even more problems. Increasing the pitch from no less than one-half pitch to full has many successful applications. However, the length of the slot over which one can feed reliably is limited to about three times the diameter ($3d$) of the screw owing to tolerances of fabrication. Another approach is to use a tapered diameter shaft where the screw's capacity increases in the discharge direction. This approach is limited as well by fabrication tolerances of the screw to $3d$.

A combination of tapered shaft diameter and increasing pitch is shown in Figure 10**a.** This allows a length-to-diameter ratio of about 6:1 instead of 3:1. A half pitch screw is used over the tapered diameter. This approach results in an excellent mass flow pattern provided that the hopper to which it attaches is also designed for mass flow.

A stepped diameter shaft screw (Fig. 10**b**) has also been developed (13) allowing even longer (up to as much as 12:1) length-to-diameter ratios. Other appropriate applications for screws are as sealing devices, multiple screws for larger openings, multiple discharge points, and as blending and cooling (or heating) devices.

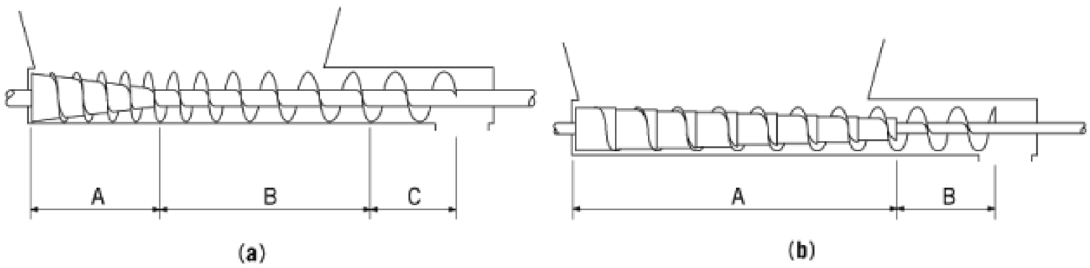


**Fig. 10.** Mass flow screw feeder designs. (**a**) Combined tapered shaft and variable pitch screw feeder where A represents a conical shaft and constant pitch (feed section); B, constant shaft and increasing pitch (feed section); and C, constant shaft and constant pitch (conveying section). (**b**) Stepped shaft screw feeder where A represents a stepped diameter shaft and constant pitch (feed section) and B, constant shaft and constant pitch (conveying section).

#### *6.1.2. Belt Feeders*

Belts are used to feed over long slotted openings. Typically, belt feeders are used to handle friable, coarse, fibrous, elastic, sticky, or very cohesive solids. Because belts are available in widths up to 2.74 m and unrestricted lengths, such feeders can be designed for very large outlets.

An improperly designed interface to the belt can cause solids compaction, abrasive wear of the belt, and excessive power required to move the belt. The preferential flow channel shown in Figure 9**b** withdraws material from one end of the outlet. Depending on the gate opening, this could be at the back or front. Some methods of providing increased capacity over the slot length are shown schematically in Figure 11. The taper in plan is not recommended for most applications because the narrow opening at the back is prone to bridging. The taper in elevation is useful but will likely withdraw material preferentially from the front.

The optimum design of a belt feeder interface is shown in Figure 12. The nose is slanted to provide stress relief as material is transferred to the discharge end. Either flat or troughed idlers may be used to train the belt. Idlers should be closely spaced so as to prevent belt sag. Skirts are also used to prevent spillage. The skirts should expand slightly in the direction of belt travel so as not to interfere with material flow. A large enough opening to prevent bridging and sloping side walls, which are steep and smooth enough for mass flow, are necessary.

#### *6.1.3. Rotary Valve Feeders*

Devices known as rotary valve feeders are commonly used for circular or square configured outlets. These are particularly useful when discharging materials to a pneumatic conveying system where a seal is required to prevent air flow through the hopper outlet. The discharge rate is set by the speed of rotation of the vanes or pockets of the valve.

A potential problem for rotary valve usage is that they tend to pull material preferentially from the upside of the valve, which can affect the mass flow pattern. Another problem is that once solid drops from the vane, the air or gas that replaces it is often pumped back up into the bin. In addition, air can leak around the valve rotor. Such air flows can decrease the solids flow rates and/or cause flooding problems. A vertical section shown in Figure 13 can alleviate the preferential flow problem because the flow channel expands in this area, usually opening up to the full outlet. To rectify the countercurrent air flow problem, a vent line helps to take the air away to a dust collector or at least back into the top of the bin.

#### *6.1.4. Louvered Feeders*

Louvered feeders, designed to withdraw material uniformly across the entire outlet cross section, can control discharge from a circular, square, or rectangular cross section using the material's natural angle of repose.

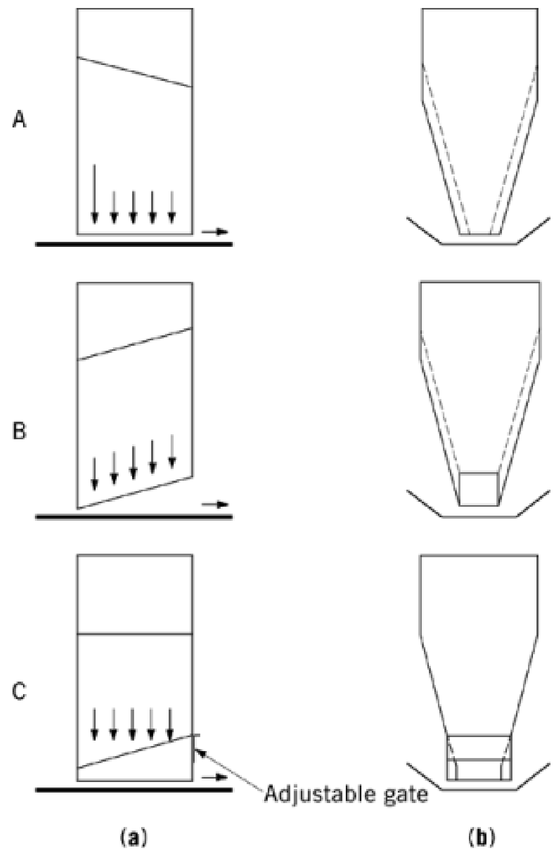


**Fig. 11.** Schematics of belt feeder interfaces to provide increasing capacity, where (**a**) shows side elevation and ( __ ) is the side view of the belt feeder on its centerline, and (**b**) shows end elevation: A, slot tapers in plan; B, slot tapers in elevation; and C, compound taper with vertical side walls.

When the drive is energized, the material's angle of repose is overcome and material discharges usually very evenly and accurately. When the drive is stopped, the material stops flowing. The design is simple, robust, economical, and has many applications.

#### *6.1.5. Vibratory Pan Feeders*

Vibratory pan devices act much in the same way as louvered feeders in that they can feed material gently and accurately. Unfortunately, they are limited primarily to applications involving round or square outlets. If a long rectangular outlet is used, the feeder must operate across the short dimension of the slot.

There are several other types of volumetric feeders that rely on external or internal agitation to initiate or maintain flow. Other types include devices that aerate material or use flexible walls that are agitated to maintain flow. These devices are all useful when used properly. However, they use something other than gravity to maintain flow and, as such, can be maintenance intensive. Knowledge of the solid's flow properties is essential to properly design the feeder. Bin opening size and hopper angles are required to ensure mass flow to the feeder. The feeder then must be capable of controlling discharge rate.

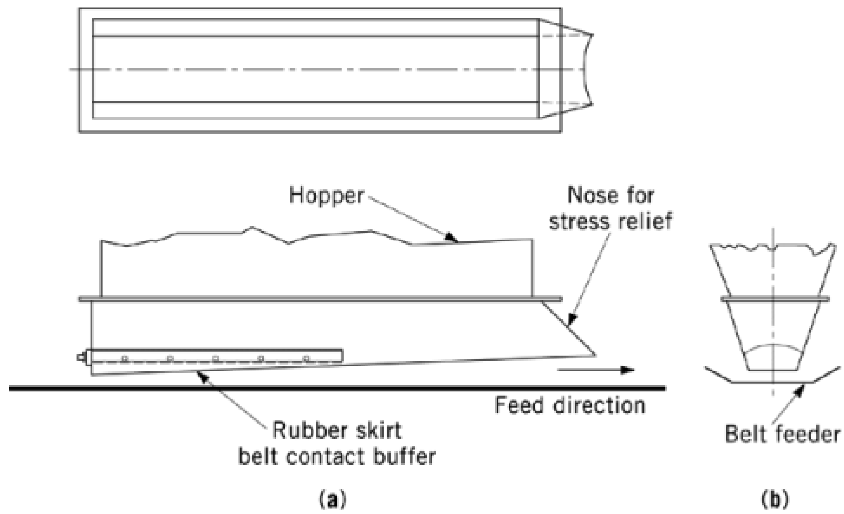


**Fig. 12.** Optimum belt feeder interface: (**a**) elevation views, where ( __ ) is the belt feeder on its centerline, and (**b**) plan view.

### 6.2. Gravimetric Feeders

Examples of gravimetric feeders are weigh belts, loss-in-weight systems, and gain-in-weight systems. Gravimetric feeders rely on weighing the material to achieve the required discharge rate. A gravimetric feeder would be used when accuracies of less than 5% are required, particularly over short time periods; when the material's bulk density varies; or when the weight of material used for a particular process needs to be recorded. There are basically two systems: continuous and batching. A continuous gravimetric system controls the weight/unit time. A batch system simply controls the weight of material discharged, such as ~40 kg of material to a mixer.

#### *6.2.1. Weigh Belt Feeders*

This type of gravimetric feeder, shown in Figure 14, typically is used in continuous feeding applications as opposed to batches. A belt feeder can be used as a weigh belt by locating weigh idlers under the belt downstream of the outlet. Load cells weigh the material crossing them and send a signal to a controller where it is integrated with the belt speed and compared to a set point. The speed of the drive is adjusted accordingly to regulate the discharge rate.

Some drawbacks to the weigh belt are that it is a zero-reference device and thus needs frequent calibration (re-zeroing). Buildup on the belt and rollers affects accuracy and operation, as does belt tension and dusty or floodable materials. Flexible connections are required to isolate the feeder from upstream and downstream equipment, unless the belt feeder/weigh idler concept is used.

#### *6.2.2. Loss-in-Weight Feeders*

The loss-in-weight (LIW) gravimetric feeder is used when feed accuracy is essential. It measures the loss in weight of material discharged from the system. As such, it can be used both in continuous and batching systems, and may be used for liquids by replacing the feeder with a pump. Load cells are attached to the bin or hopper that are capable of weighing the bin, feeder, and the contents. These load cells sense changes that take place as material is discharged and send a signal to a controller to speed up or slow down the feeder.

A disadvantage of LIW systems is that they cannot weigh while being filled. A typical LIW system switches to volumetric feeding while the filling process occurs, and when the bin is filled, it switches back to gravimetric.

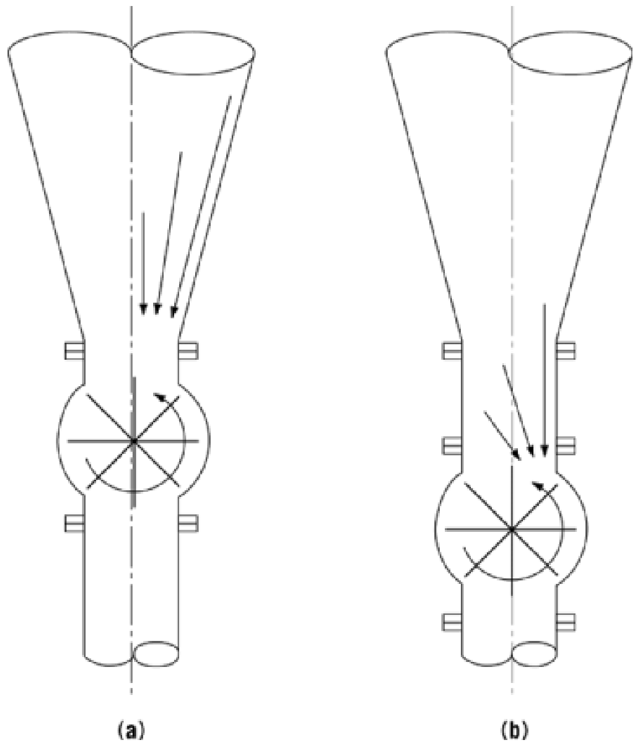


**Fig. 13.** (**a**) Preferential flow through rotary valve and (**b**) correction from installation of a vertical spool piece.

Some systems are available with no-freeze designs in which one bin and feeder discharges while another is being filled, and these are easily switched back and forth. Screws, belts, rotary valves, and louvered or vibratory pan feeders can be used to control discharge.

#### *6.2.3. Gain-in-Weight Feeders*

These types of feeders are used only for batching applications. The receiving container rests on a scale or on load cells and the system controls the discharge from the filling bin, which can use a volumetric feeder to control rate. A batch accuracy of $\pm 1/4\%$ at two standard deviations is not unusual.

## 7. Special Considerations

### 7.1. Particle Segregation Mechanisms

Segregation is the process by which an assembly of solid particles separates as it is being handled. This often results in costly quality control problems due to the waste of raw or finished materials, lost production, increased maintenance, and capital costs required to retrofit existing facilities.

Segregation problems occur in a wide range of industries handling materials as diverse as coal (qv) and pharmaceuticals (qv). The cost implications can be great, even when handling small quantities of material. In the batch processing of pharmaceutical tablets, it is not unusual for the value of a single batch of ingredients to be in excess of $100,000. Strict U.S. quality control standards dictate that some or all of the batch may have

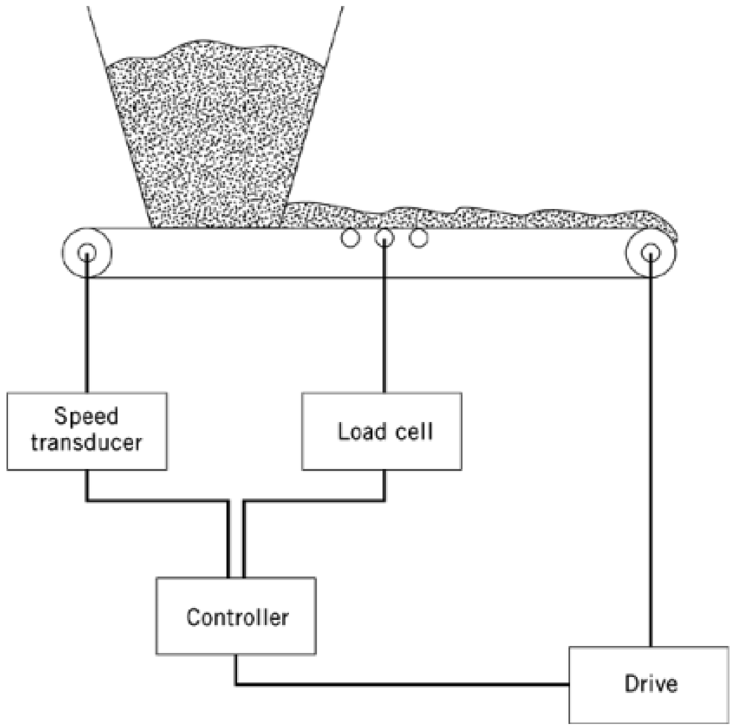


**Fig. 14.** Weigh belt feeder.

to be discarded if it is found that the amount of active ingredient or total weight of just five tablets in a batch varies outside narrow limits.

The primary mechanisms responsible for most particle segregation problems are sifting, particle velocity, air entrainment, particle entrainment, and dynamic effects (14).

#### *7.1.1. Sifting*

The movement of smaller particles through a mixture of larger ones (sifting) is the most common mechanism by which particles segregate. In order for this mechanism to occur, all of the following conditions must be present: (*1*) a difference in particle size, ie, a difference smaller than 2:1 can cause sifting segregation; (*2*) a sufficiently large mean particle size, ie, sifting segregation is more common in mixtures having a mean size greater than 100–200 $\mu$m; (*3*) free-flowing material, ie, the lesser the tendency for particles to adhere to each other, the more likely they are to segregate; and (*4*) interparticle motion, eg, due to formation of a pile or movement of material on a conveyor.

Sifting may occur while a pile is being formed. Fine particles are concentrated in the center under the fill point. However, as the pile is formed, the slope stability is such that layers of finite thickness intermittently move from the central fill point, carrying some of the finer particles with them.

#### *7.1.2. Particle Velocity on a Surface*

Smaller particles, those that are more irregular in shape and/or those that have a higher surface roughness, typically have a higher frictional drag on a hopper or chute surface.

On a chute, higher drag results in lower particle velocity which can be accentuated by stratification on the chute surface because of the sifting mechanism. Concentrations of smaller particles close to the chute surface and larger particles at the top of the bed of material, combined with the typically higher frictional drag of finer particles, often result in a concentration of fine particles close to the end of the chute, and coarse particles farther away. This can be particularly detrimental if portions of the pile go to different processing points, as is often the case with multiple outlet bins or bins with vertical partitions.

#### *7.1.3. Air Entrainment*

Fine particles generally have a lower permeability than coarse particles, and therefore tend to retain air longer in void spaces. Heavier particles settle more quickly in a fluidized mixture than lighter particles. Thus, when a mixture of particles is charged into a bin, it is not uncommon to find a vertical segregation pattern, where the coarser, heavier particles concentrate at the bottom of the bed and the finer, lighter particles concentrate near the top.

#### *7.1.4. Entrainment of Particles in an Air Stream*

The lighter the particle and the finer its size, the longer it may remain suspended in an airstream such as upon filling of a bin. Secondary air currents can carry airborne particles away from a fill point into outer areas of a bin, scattering them in a way that bears no resemblance to the calculated trajectory.

Particles may also be affected by air resistance as they fall, resulting in finer particles having a lower free-fall terminal velocity than coarser particles and thereby not traveling as far horizontally when they exit a chute. However, a stream of particles drags a stream of air with it, preventing the full drag force from being felt on individual particles. Thus, only particles on the edge of the stream are affected by air drag.

#### *7.1.5. Dynamic Effects*

Particles often differ in their resilience, inertia, and other dynamic characteristics which can cause them to segregate, particularly when they are forming a pile such as when charged into a bin or discharged from a chute.

### 7.2. Correcting Particle Segregation

The main techniques to consider when segregation problems are present are to change the material, change the process, or change the design of the equipment.

#### *7.2.1. Properties of the Material*

A common characteristic of most highly segregating materials is that they are free flowing, and therefore the particles easily separate from each other. Thus, one way to decrease segregation tendencies of a material is to increase its cohesiveness by, for example, adding water or oil. If overdone, other flow problems such as arching or ratholing may replace segregation, potentially resulting in an even greater disruption to the process.

Another technique is to change the particle size distribution. There are, however, disadvantages. If segregation is occurring by the sifting mechanism, the particles must be almost identical in size before sifting is prevented. Alternatively, the mean particle size can be reduced below 100 $\mu$m, but this size reduction (qv) increases the probability of segregation by the too fine powder mechanisms.

#### *7.2.2. The Process*

If a mixture is handled that consists of several ingredients, which are more or less uniform in themselves but vary distinctly from one to another, each ingredient should be handled separately up to the final processing step, then proportioned and mixed just before this step. When pneumatically conveying a fine fluidizable powder into a bin, a tangential entry into the side of the bin should be used rather than going in at 90$^\circ$ either to the side wall or the top.

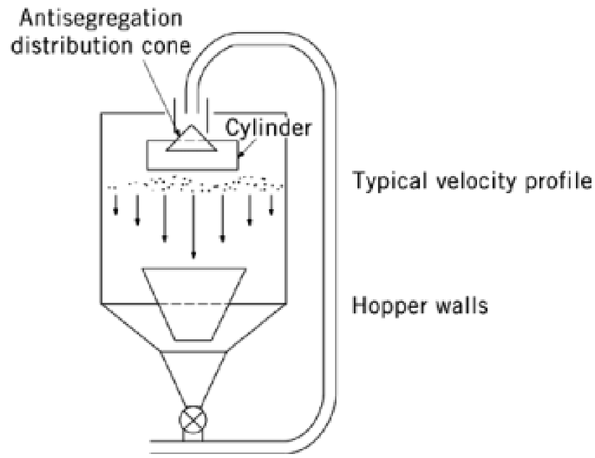


**Fig. 15.** BINSERT in-bin blender. The hopper walls are chosen to cause a significant velocity differential center to the outside.

#### *7.2.3. The Design of the Equipment*

If materials have segregated from side to side while filling a bin, a mass flow pattern tends to minimize segregation upon discharge, whereas a funnel flow pattern makes the segregation worse. Increasing the height-to-diameter ratio of the cylinder section of a mass flow bin above 1.0 usually results in a uniform velocity pattern across the top surface. This lessens the tendency for segregation compared to using a short cylinder section or only a converging hopper.

When segregation is a concern, a single-outlet, symmetric bin should be used. However, if a multiple-outlet bin is required, the hoppers and outlets should be located symmetrically with respect to the fill point to prevent concentrations of fines in one hopper section which could cause pluggage or downstream quality control problems.

An alternative to traditional mass flow bin design is to use a patented BINSERT, which consists of a hopper-within-a-hopper below which is a single-hopper section (Fig. 15). The velocity pattern in such a unit is controlled by the position of the bottom hopper. A completely uniform velocity profile can be achieved which results in an absolute minimum level of segregation. Alternatively, by changing the geometry at the bottom of the hopper, a velocity profile can be developed in which the center section moves faster than the outside, thus providing in-bin blending of the materials (7).

### 7.3. Fine Powder Flow Phenomena

A fine powder is a material where the flow behavior is significantly influenced by the effects of entrained gas in its void spaces. This is in contrast to a coarse material such as plastic pellets in which the voidage is so great that gas effects can be neglected. Thus, for example, the limiting steady flow rate through an orifice can be described by equation 2 in which interstitial gas effects are ignored. For a fine powder such effects are extremely important, causing, for example, the maximum flow rate of such a material through a mass flow bin outlet to be several orders of magnitude lower than predicted by equation 2.

When handling a fine powder in a bin, funnel flow, mass flow, and fluidized handling can be considered (15). Funnel flow is seldom recommended because discharge is so unpredictable, ie, from no flow owing to arching or ratholing, to uncontrolled flow owing to flooding. With mass flow, discharge is controlled and predictable, but the rate is limited. Fluidized handling is generally only practical if the powder is easy-flowing and has relatively low permeability. Although high rates of discharge are possible, the powder's bulk density is much lower and more variable than if gravity-driven mass flow is used.

For a mass flow bin, one of three flow-rate dependent modes of discharge can occur. (*1*) Steady gravity flow of partially deaerated material controlled by a feeder is most desirable. The limiting condition occurs when compaction in the cylinder section of the bin forces too much gas out through the material top surface. Because a bulk solid expands while flowing through the converging portion of a bin, a slight vacuum develops in its voids which causes a gas counterflow through the bin outlet that forces the solids contact pressure to drop to zero and limits the steady solids flow rate. (*2*) This mode occurs at flow rates somewhat greater than the limiting rate and is characterized by an erratic, partially fluidized powder discharging from the bin which can be controlled by some types of feeders. Even better, a steady rate can often be achieved by using an air permeation system at an intermediate point in the bin to replace the lost gas, increasing the outlet and corresponding feeder size, adding a standpipe between the bin outlet and feeder, and/or lowering the bin fill level. (*3*) This mode of flow occurs when the flow rate is too high to allow much, if any, gas to escape from the void spaces. In this extreme, the material may be completely fluidized and flood through the outlet unless the feeder can control fluidized powder.

Testers are available to measure the permeability and compressibility of powders and other bulk solids (6). From such tests critical, steady-state flow rates through various outlet sizes in mass flow bins can be calculated. With this information, an engineer can determine the need for changing the outlet size and/or installing an air permeation system to increase the flow rate. Furthermore, the optimum number and location of air permeation levels can be determined, along with an estimate of air flow requirements.

### *7.3.1. Fluidized Handling of Powders*

Sometimes it is more practical to handle fine powders in a fluidized state rather than to deaerate the particles and handle by gravity alone. Through the use of air pads, air slides, and/or air nozzles, some or all of the contents of a bin can be fluidized. This overcomes the common no-flow problems of arching and ratholing, and allows discharge rates through bin outlets several orders of magnitude faster than if the powder is deaerated.

When evaluating fluidized handling several factors must be considered. (*1*) The powder must have low cohesive strength, otherwise channels are likely to form which prevent uniform fluidization. In addition, it is helpful if the powder has low permeability so as to limit the amount of gas needed for fluidization as well as allow retention of the gas when it is turned off. (*2*) The bulk density of the powder as it exits the bin will be low and nonuniform, thus it may not be possible to fit the required mass of material into a downstream container, eg, a truck or rail car. If the powder is being fed into a process and close control of flow rate is important, the nonuniformity of bulk density may create significant control problems. (*3*) The cost of energy required to fluidize the bin may be significant, particularly if dry air must be used because the powder is hygroscopic. (*4*) Particle segregation may be made worse. Simply putting an air pad or an air slide into a bin is likely to segregate a powder, causing a vertical striation pattern with fine, light particles on top and dense, large particles on the bottom. (*5*) The amount of bin volume necessary to be fluidized must be evaluated. If possible, the entire contents should be fluidized, but this may be neither practical nor necessary, particularly if the bin is relatively large. If only a portion of a bin is fluidized, the potential for stagnant material supporting a rathole may be a concern. Void space must be provided for the material to expand. (*6*) What to do with the fluidizing air when there is no powder discharge taking place must be considered. If the powder becomes cohesive when it is deaerated, refluidization is difficult. Intermittent fluidization during periods of no discharge may be necessary.

### *7.3.2. Purge and Conditioning Vessels*

Vessels designed for processing solids are often adaptations of conventional storage bins modified to achieve the desired process activity. A wide variety of solids including chemicals, plastics, and sugar are processed in this way. Some of the processes carried out include heating, cooling, polymeric phase transformation, drying, curing, and suppressing or enhancing a particular chemical reaction.

Purge and conditioning vessels often exhibit nonuniform purge of conditioning which may be the result of nonuniform solids or fluid (gas or liquid) velocity profiles causing the solid's exposure time to the fluid to be nonuniform; cross-contamination, particularly after grade changeovers, which can easily happen unless the solids flow sequence is first-in/first-out; no flow due to formation of a stable obstruction at the outlet of the vessel or a rathole; erratic flow which involves fluctuations in either flow rate of bulk density; or segregation which creates quality control problems in the final product.

The key to solving these problems is to design the vessel for a mass flow pattern. This involves consideration of both the hopper angle and surface finish, the effect of inserts used to introduce gas and control the solids flow pattern, and sizing the outlet valve to avoid arching and discharge rate limitations. In addition, the gas or liquid must be injected such that the solid particles are uniformly exposed to it, and flow instabilities such as fluidization in localized regions are avoided.

### 7.4. Mixing and Blending

Quality control is more important in the 1990s competitive global economy than ever before, and blending is a useful technique by which quality is improved. Improving uniformity of a raw material stream which enters a process, or the output stream from a process, can be extremely helpful. Static in-bin blenders are sometimes used to dampen upsets either going into or coming from a process, while batch and tumble blenders are sometimes used for close, well-defined quality control (see Mixing and blending).

#### *7.4.1. Requirements for Static in-Bin Blenders*

An in-bin blender consists of basically a storage bin or silo which doubles as a blender (16). Requirements to make such a blender effective include no stagnant regions, ie, mass flow design; large velocity gradients throughout the blender, ie, the differential between the time it takes a particle in the fastest flowing region to exit the blender compared to a particle in the slowest flowing region should be as large as possible, and particles in the fastest flowing region should start to discharge as soon as possible after entering the blender; minimum need for recirculation to provide blending; blending uniformity independent of the blender's fill and discharge rates as well as level of material; the ability to blend a wide variety of materials, eg, fine and coarse particles, free-flowing, and cohesive materials; the ability to prevent segregating materials from demixing as they discharge from the blender; and cost effectiveness.

#### *7.4.2. Multitube Blenders*

These blenders, eg, the Phillips and Young type, are widely used to blend materials that are free-flowing, uniform in size, and have low angles of internal friction.

Some problem applications for multitube blenders include blending in a small amount of additive; materials that contain a wide range of particle sizes, because sifting segregation can cause fines to percolate through the coarse particles while flowing toward a tube opening causing the fines to discharge last; materials that have high angles of internal friction, because flow problems in the tubes and steep flow channels outside the tubes can result and this can severely limit blending; cohesive, ie, nonfree flowing materials that may cause pluggage to tube openings; and fine powders which tend to aerate and flood through the tubes because of brief retention times.

#### *7.4.3. BINSERT Blenders*

The design of a BINSERT blender consists of a hopper-within-a-hopper, both of which are usually conical in shape (Fig. 15). Particles flow through the inner hopper as well as through the annulus between the inner and outer hoppers. By varying the relative position of these two hoppers as well as the configuration of the outlet

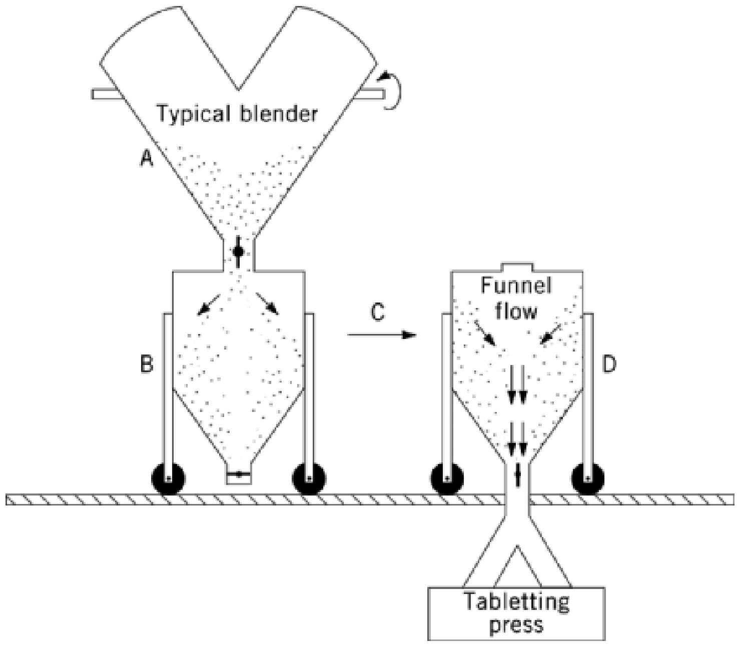


**Fig. 16.** A typical batch blending operation. See text.

geometry, it is possible to achieve between a 5:1 and 10:1 velocity differential between particles in the inner hopper compared to particles in the outer annular region (7, 17).

Although a BINSERT blender often requires more recirculation to achieve an acceptable blend than a multitube blender, it has a number of potential advantages including ease of cleaning since all of the internal parts are exposed and accessible; blending cohesive, ie, nonfree-flowing materials since the outlet can be sized as large as necessary for flow; blending materials with high angles of internal friction and materials which are highly segregating, eg, containing a wide range of particle sizes; low headroom requirements since the walls of the outer hopper can be made relatively shallow; no mechanical moving parts other than perhaps a feeder, eg, belt, screw, or rotary valve used at the outlet to control the discharge rate, and a recirculation system; and it can often be retrofitted to an existing storage bin causing it to act as an in-bin blender.

#### *7.4.4. Batch Blending*

A typical batch blending system is shown in Figure 16. The basic components are a blender, one or more portable or stationary containers, and a chute to a process, eg, a tabletting press. A typical operation consists of mixing the ingredients in the blender, A, discharging the blend into a container, B, which is then moved into position over the chute, C, and gradually discharging the blend into the process, D.

Solid–solid blending can be accomplished by a number of techniques. Some of the most common include mechanical agitation which includes devices such as ribbon blenders, impellers, paddle mixers, orbiting screws, etc; a rotary fixed container which includes twin-shell (Vee) and double-cone blenders; and fluidization, in which air is used to blend some fine powders.

An important aspect of the performance of these blenders is the sequence of loading the batch to achieve optimum performance. As material discharges from a blender into a portable or stationary container, demixing or segregation often occurs. Typically, segregation due to sifting, fluidization, or entrainment of fine particles in the air takes place depending on the rate of discharge and the particle size distribution of the blend.

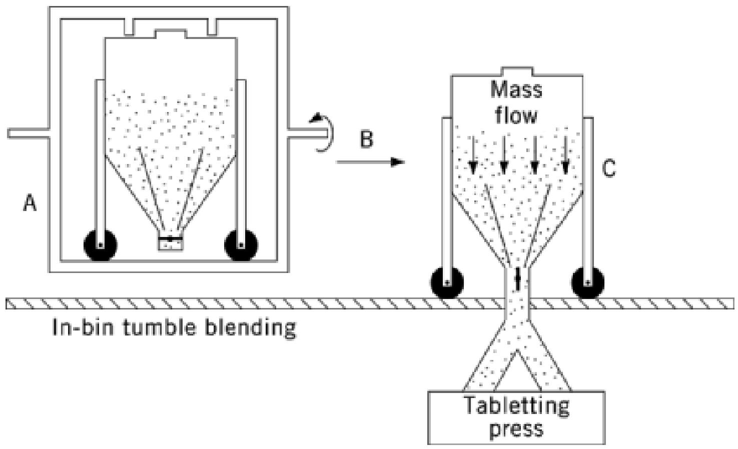


**Fig. 17.** Tumble blend operation using portable BINSERT containers where A represents the blend stage; B, transport; and C, discharge.

The flow pattern that develops as the material discharges from the portable or stationary container strongly influences what effect, if any, the filling segregation has. In many systems the container promotes a funnel flow pattern. Upon discharge, the material in the center, which is often predominantly fines, is discharged first. Mass flow eliminates this problem; however, if the blender discharge is segregated, mass flow locks in the sequence of fines and coarse product as they exit the blender.

#### *7.4.5. Tumble Blending*

Tumble blending has a number of advantages over other common blending techniques. First, it eliminates having to discharge the blender into a portable or stationary container. Thus, at the end of the blending cycle, the material in the container is blended avoiding segregation that can take place during filling. Second, tumble blending eliminates the costly step of blender cleaning between batches. All the material is confined within the portable container, so when cleaning is required only the container needs to be cleaned, not the stationary blender. Third, tumble blending eliminates downtime required to fill and empty a blender, because the tumble station is ready to accept a new container as soon as the previous one has finished tumbling. Other advantages include maintaining strict batch integrity, minimizing dust, and providing more throughput since one tumble station can service different materials.

Problems of segregation, no-flow/erratic flow, flooding, etc, must be minimized if not eliminated, therefore containers designed for mass flow as opposed to funnel flow are preferred. The BINSERT has significant advantages over standard mass flow designs, which are particularly useful in tumble blending applications (Fig. 17) (18).

#### *7.4.6. Flow Aids*

Flow aids are devices used to assist in discharging materials from a bin or other storage container. The best use of such a device is when gravity alone is insufficient or impractical to provide reliable discharge. However, in many instances, flow aid devices are overused in applications in which they are either unnecessary or create new problems.

Flow aids can generally be divided into three categories: mechanical, eg, those that rely on vibration or agitation of the material, such as vibrating dischargers, external vibrators, rotating arms, vibrating panels, etc; introduction of air, eg, air cannons, air slides, or air nozzles; and chemical, eg, fumed silica. Some flow aids rely on a combination of these types.

#### *7.4.7. Vibrating Dischargers*

These mechanical devices, sometimes called bin activators, consist of an outer shell to which one or more motors with eccentric weight are mounted. By hanging the unit from the bin and using a rubber gasket to prevent spillage, the unit vibrates in a horizontal motion to assist in discharging material. The vibration is transmitted to material inside the unit through the use of a central baffle, which is either dome-shaped or conical, and supported by beams which are welded to the outer vibrating shell.

The area of influence of a vibrating discharger is limited to a cylinder, the diameter of which is roughly equal to the top diameter of the discharger. Hence, if a vibrating discharger is mounted onto a conical hopper section, flow is confined predominantly to a central flow channel located directly above the discharger. This is true unless the slope and smoothness of the static cone meet requirements for mass flow, or the diameter of the flow channel exceeds the critical rathole diameter for the material.

A vibrating discharger is incapable of controlling the rate of material discharged from it, ie, it is not a feeder. Therefore, if feed rate control is required, some type of feeder, eg, screw, rotary valve, or vibrating pan, must be mounted below the discharger's outlet. To avoid overcompacting the material by trying to force it to flow at a rate higher than that of the feeder, it is often necessary to cycle the discharger on and off using a field-adjusted timer. It is important that a vibrating discharger be operated on a regular basis, not just when complete discharge of the bin is required, otherwise the flow channel may locate preferentially on one side of the bin, which can cause significant structural problems resulting from nonuniform loading on the bin walls. If the material being handled is pressure sensitive or if segregation is important, the use of a vibrating discharger may not be advisable.

#### *7.4.8. External Vibrators*

Air- and electrically operated mechanical vibrators are sometimes placed on the exterior of hoppers and chutes. The type of vibration transmitted can vary from a high frequency, low amplitude mode, to a low frequency, high amplitude thumping condition. In general, such devices are better suited to cleaning off chutes than for use on hoppers to be filled with bulk solids. Disadvantages include noise pollution and possible fatigue damage to the structure.

#### *7.4.9. Air Blasters*

Air cannons, or air blasters, consist of a cylinder of compressed air that has been pressurized, typically to plant air conditions 0.55–0.69 MPa (80–100 psi). When the unit is fired, a quick-acting valve is opened allowing the air to quickly exit the blaster and enter the bin. Such devices can be effective in collapsing a stable arch, but are usually far less effective in breaking up a stable rathole. If the material is severely caked, firing an air blaster into it may cause the material to shatter into large chunks, making subsequent firing of the air blaster ineffective because the air has a convenient path by which to dissipate its energy.

The effective range of a typical air blaster is on the order of 1.8–2.4 m. If a single air blaster does not provide sufficient energy to break an arch, multiple units can be used. These are fired simultaneously if at the same elevation, then start sequentially from lower elevations in the hopper and work upward.

When firing an air blaster, the pressure in the chamber is initially felt at nearly its maximum value in a localized area of the bin wall around the blaster nozzle which may require reinforcement to take the pressure.

#### *7.4.10. Mechanical Agitation*

Devices consisting of a horizontal or vertical shaft with arms may be used to break up material and thereby cause it to flow. However, if the force resisting movement of such devices is large enough it can render the device useless either because of insufficient power to turn it or enough power to cause it to self-destruct. In general, such devices should only be used in relatively small bins and hoppers.

Other types of mechanical agitation consist of vibrating screens or expanded metal panels. However, if the device fails to perform for any reason, discharging material from the bin will be much more difficult than if the device were not present.

Uniform, reliable flow of bulk solids can allow the production of quality products with a minimum of waste, control dust and noise, and extend the life of a plant and maximize its productivity and output. By conducting laboratory tests and utilizing experts with experience in applying solids flow data, plant start-up delays that can impact schedule and cost can be eliminated.

Existing facilities present daily bulk solids flow problems; solids flow testing and analysis saves many hours of expensive downtime and thousands of dollars, thus moving from the complication of quick-fix solutions that are not satisfactory, to proven engineering solutions that work every time.

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