Technical Paper

Bin Design: a Summary Report

Bins may perform a simple function, but their design is crucial to keeping process material on the move

Anyone who has had to resort to sledgehammer blows to persuade materials to flow from a bin knows of the complexities and difficulties of bin design. Before the physics of material storage and flow was even marginally understood, such a heavy-handed approach mainly served to characterize the frustration in solving the apparently simple problem of making material move from a container with a hole in the bottom. Simple problems don't always have simple solutions, though. Getting material to obey the law of gravity can be a perplexing case in point.

No less perplexing is the realization that virtually every variable in bin design holds potential veto power over the workability of the entire system. Not only does bin geometry play a determining role, but so do the varied physical properties of the material. The downstream device into which the material flows must be given its due consideration or problems may follow; even the elements of time and environment can spell disaster.

The bright side of this complicated picture is that material flow headaches are, in fact, avoidable. Many material handling experts agree that the vast majority of storage and flow problems they see could have been prevented if compromise and lack of knowledge did not dominate the crucial design stage.

A great deal has been written about bin design -- far too much to cover in exhaustive detail here. However, as a summary report of sorts, this paper will attune you to some of the basic considerations of bin design, and provide you with a foundation upon which to build the specialized knowledge you'll need to guarantee success.

Problems, Problems

When careful consideration isn't given to bin design, it's just a matter of time before problems crop up. Designing a bin only on the basis of desired capacity or available headroom can cause the no-flow conditions of arching or ratholing as shown in Figure 1. In domino-like fashion, other problems inevitably arise:

a) Irregular flow resulting from the cyclic formation and collapse of arches or ratholes causes wide swings in material density which, in turn, degrade feeder response.
b) Aeration following collapse can cause uncontrolled material flooding.
c) Substandard remixing of segregated particles occurs following collapse (in segregation, larger and heavier particles fall to the bin walls during loading).
d) Inaccurate level measurement results when ratholes happen. Weighing the entire bin is about the only option if accurate measurement is needed.

These and other problems can be a continual reminder of poor flow system design; process inefficiencies and their costs persistently mount, and can quickly outweigh any conceivable economy of casual or compromised design.

Material in Motion

Basically, material flow from bins falls into three categories: funnel flow, mass flow, and expanded flow. Each is appropriate for a particular set of material characteristics and process requirements.

Funnel Flow - Funnel flow bin design is often the best approach for materials which are coarse, dry, do not pack or deteriorate, and where segregation is not a problem. Figure 2a shows typical funnel flow. Here, material flows from the bin in a last-in/first-out manner where material sloughs off the inwardly sloping top surface, falls down the central channel and through the outlet. Since material located away from the zone extending vertically above the outlet may not flow spontaneously, outlet dimensions must be characteristically large.

Owing to their relatively abrupt hopper constriction, large diameter, and long, upright walls, funnel flow bins have a high storage capacity for their size. However, effective capacity is reduced somewhat by whatever dead storage volume may occur, hence the caution against using funnel flow designs for materials that cannot endure potential long term residence without a problem.

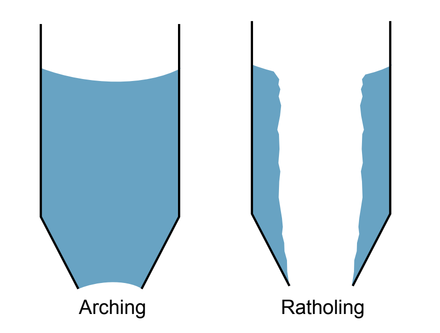

Figure 1 - Arching and ratholing

As is easily seen by comparing the funnel flow pattern in Figure 2a to the rathole condition in Figure 1, the difference is slight, except that in one material flows and in the other it doesn't. Ratholing can be avoided in funnel flow bins by selecting the right bin geometry, but there remains a limiting constraint regarding the percentage of fines: if the material contains more than 15-20% of fines by weight, the spaces between the coarse grains may become filled with fines during loading and settling, deaerating the material to the point where the material near the bin walls becomes strong enough to support its own weight. A rathole may then result.

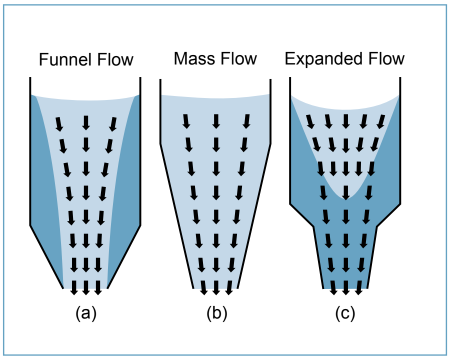

Figure 2 - Flow types in bins

Mass Flow - Unlike funnel flow, all material in mass flow is in constant downward motion during discharge (Figure 2b). Mass flow bins are mainly characterized by comparatively long, steep, gently tapering hopper walls. Flow occurs in a first-in/first-out manner. Without any abrupt constriction, mass flow bins are innately less prone to present the flow problems of their funnel flow counterpart. However, design consideration must still be given to these problems if they are to be steadfastly avoided.

In mass flow, materials which segregate during loading are efficiently remixed in the hopper during discharge. Dead storage and the consequent risk of material degradation are eliminated, as are the uncertainties of level measurement present in funnel flow. Also, because discharged material falls from the outlet plane in mass flow (as opposed to the greater height from which material falls in funnel flow), outlet velocity is comparatively low and does not vary much with material level, a benefit when discharging to a feeder. All but the most moderate variations in material density are avoided in mass flow, another especially preferred condition when discharge is to a feeder. Finally, flooding of fine material, a possible problem in mass flow, can be easily avoided by maintaining a minimum level in the hopper.

Evidently, there are many pluses tot he mass flow approach; however, a physical consideration may prevent its application. The price paid for the benefits of mass flow is relatively greater height and more limited storage capacity, compared with the funnel flow approach. Thus, the application's available headroom and minimum storage volume must be considered in choosing between these two design approaches.

Expanded Flow - A hybrid of mass and funnel flow, expanded flow results from the combination of funnel flow and mass flow design aspects (Figure 2c). Expanded flow is especially appropriate for large capacity and high discharge rate applications. The large diameter of the upper section provides maximum storage volume, while the lower section is widened to prevent arching and ratholing. Expanded flow is used for many hard to flow and dry materials. As a hybridized design, remixing of segregated particles is better than in pure funnel flow, but not as good as in straight mass flow designs. Also, outlet velocities fall somewhere between the faster funnel flow and the slower mass flow types.

Foiling the Arch Enemy

To a large extent material characteristics, process requirements and available space will indicate the bin type best suited to the job. But within each approach many design variables must be addressed, all concerned with ensuring that gravity never fails to win out over the potentially self-supporting strength of the confined material. To illustrate, consider arching.

In arching, the consolidated material's strength by definition prevails over the pull of gravity. The arch successfully supports the material above it. Like any arch, an arch made of consolidated bulk material maintains itself by effectively diverting a portion of the applied (downward) weight force to a horizontal force applied to bin walls. Even intuitively, it is clear that large arches sustain larger stresses than small arches; thus, the stress carried by an arch is related to its size or span.

Arching can be eliminated, then, simply by sizing the hopper outlet so that the material's strength is never enough to support an arch of that dimension. To do that we must first know more about the strength of the material under a compacting or consolidating pressure, and, in turn, how consolidating pressure changes with the depth of the material in the bin.

Figure 3 shows a bin charged with material. Any bulk solid has, unlike an inviscid liquid, some ability to withstand shear stress, even when no consolidating pressure is present. This innate material strength (f_o) is shown where consolidating pressure (p) is non-existent at both zero depth and theoretical hopper vertex. As depth increases so does consolidating pressure, quickly through the shallower but more slowly at greater depths. A tapering off of depth-related increases is expected though, because greater consolidation causes greater material strength. In circular fashion, the greater the material's strength, the better able it is to structurally support the load applied by the weaker and less consolidated material above it.

At the transition from vertical to tapering walls another expected change in consolidating pressure is observed: an abrupt, steplike pressure increase contributed by the impending constriction. At even greater depths consolidating pressure, which must decline to zero at the hopper vertex, drops off linearly.

Material shear strength (f) approximates the pattern of consolidating pressure in rough form, if not in magnitude. Such a relationship stands to reason: different materials will gain strength at different rates under pressure, but all will, within limits, gain strength as consolidating pressure grows.

To find the smallest outlet that won't support an arch, all that remains is to determine the point at which the material's strength just equals the net combined stress applied to the material by flow-inducing gravity and flow-retarding hopper geometry. This stress (s) is plotted in the figure. Where bin walls are vertical and do not support the material (except for frictional forces which are ignored here for simplicity), the net flow-inducing stress is at its greatest. The stress declines beginning at the hopper transition and falls linearly to zero at the vertex as a function of the straightly tapering walls in this example. The critical hopper opening, therefore, occurs at the depth at which material strength overtakes the net flow-inducing stress. At any greater depth the material will be able to support itself with an arch.

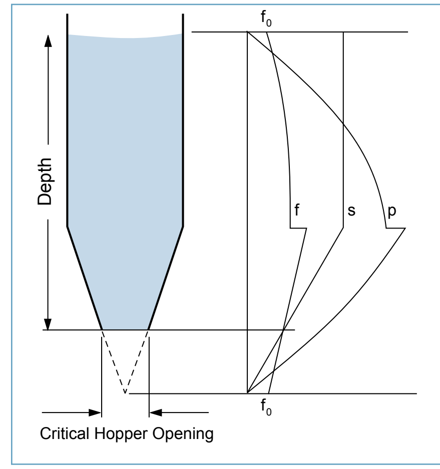

Figure 3 - Strength and pressure in bins

Getting Specific

In the above example bin geometry was fixed, and no specific values were assigned to the relationship between material strength and consolidating pressure. In reality, though, it's the other way around: bin geometry is unknown at the outset, while the material strength/consolidating pressure relationship is readily determinable.

To quantify that relationship, known as the flow function (Figure 4), a shear tester is used. This device measures material shear strength under various applied consolidating pressures, resulting in the empirical values required to plot the flow function (recognizable as a portion of Mohr's stress circle). Material density, moisture content, particle size distribution, ambient temperature, and time under pressure are all potentially variable in practice, so strength measurements must be made over the entire expected range of these properties and conditions.

A note of caution: Properties of materials obtained from different suppliers can vary widely. Thus, a reasonable and conservative approach to bin design would require testing materials from not only the primary source, but also alternative suppliers as well. Clearly, knowing all facets of the material's characteristics is central to the design of an effective bin.

Once the flow function is plotted, attention can be turned to determining hopper geometry. To form a measure of the flowability of a particular hopper, the ratio of the consolidating pressure and the flow-inducing stress, called the flow factor, is used. Flow factors for a wide range of hopper designs have been developed and are available by referring to "Storage and Flow of Solids" by A W Jenike; Bulletin No. 123, Utah Engineering Experiment Station, University of Utah, Salt Lake City, Utah.

With a flow factor for a candidate hopper plotted in Figure 4, the flow factor/flow function intersection determines the point at which material strength equals the net flow-inducing stress, our arch-avoidance criterion. At consolidating pressures to the left of the intersection, the flow function exceeds the flow factor, and flow cannot result; at pressures to the right of the intersection, the stress promoting flow is greater than the stress (strength) resisting it, so the material flows. With hopper geometry treated by the flow factor, and minimum hopper outlet specified by the flow function/flow factor intersection, hopper geometry in this simplified example is determined.

The mere specification of a bin design based on the avoidance of any single problem is obviously not enough, however. A bin is no small investment, and its contribution to the efficiency or inefficiency of a process is great. Thought must be given to the adequacy of discharge rates, loading schemes and settling times, venting and containment, and the compatibility of the bin's material of construction with the material(s) it is to contain. These and other considerations underscore the need to plan with Murphy's law in mind.

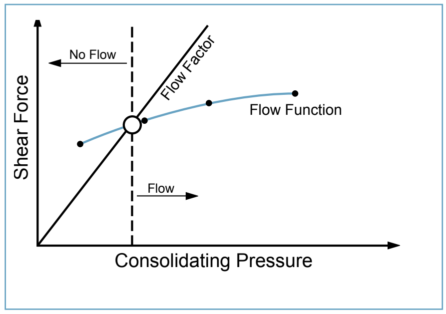

Figure 4 - Determining hopper geometry

A Word on Flow Aid

In many cases the telltale sign that a bin's design was compromised is the overuse of flow aid devices. While it would be plainly wrong to place a blanket indictment on the use of such devices, it is true that proper bin design would make their use unnecessary in quite a number of instances. Certainly, existing bins are often economically refitted with a flow aid device to enable them to accommodate materials for which they were not originally intended. The point, though, is this: When designing a new bin or hopper section, flow aid devices should not be considered the prime or necessarily most economical solution to handling difficult materials. Care exercised in design can often prevent the complication, expense and maintenance involved in any flow aid device.

Conclusion

Although still a complicated exercise requiring full knowledge of both material and method, proper bin design quickly and continually returns its cost in the form of reliable smooth and consistent material flow. The direct benefits of a well-thought-out bin design range from increased production and improved product quality to better efficiency of process equipment, less maintenance, a cleaner plant and fewer surprises at start-up. Even in only skimming the subject's surface, it is clear that bin design commands a priority commensurate with its importance in the process.

To download other papers in this series, or for more information on Coperion K-Tron equipment and services, please visit

www.coperion.com