To determine the hopper angle for a bulk solid material, you must account for the weight of the material bed above the cone section and determine the material's internal angle of friction. The internal angle of friction is determined by shear stress testing (using a testing device such as the Jenike Shear Tester or the Ring Shear Tester). These tests apply consolidation pressure to a material sample to simulate the material bed's pressure in the hopper. Since some surfaces allow particles to slide more easily than others, the tests can also determine the material's wall friction coefficient using the same material type that makes up the hopper wall. The internal angle of friction is also used to determine the material's required hopper discharge opening size.

This friction comes with a price, however. Interparticle friction can lead to reduced or irregular material flow or even blockage and must be considered when determining the angle for a hopper’s bottom cone section (called the hopper angle). Too often, hoppers are designed using the material’s angle of slide or angle of repose to determine the hopper angle, but these angles only indicate the material's flow behavior when the material is unconfined, not when the material is confined in a hopper.

In a bulk solids hopper, interparticle friction can work both for and against you. Interparticle friction provides some support for the material bed. The wall of a bulk solids hopper doesn’t need to be as strong as the wall of a fluid vessel holding the same material height because the horizontal pressure placed on the wall by a bulk solid material isn’t as great as the hydrostatic pressure generated by a fluid, as shown in Figure 1. Hydrostatic pressure increases linearly with the height of the fluid material, but interparticle friction and friction from the hopper wall causes the horizontal pressure in a bulk solids hopper to increase at a much slower rate. As a result, a bulk solids hopper doesn’t need the same structural integrity as a fluid storage vessel, which significantly reduces capital costs.

Some materials consolidate over time, which increases the internal...
angle of friction in the hopper and the material’s resistance to flow if the material stays at rest too long. Shear testing can determine your material’s compressibility, or its susceptibility to time consolidation. This is done by storing material samples with weights added to simulate the material column in the hopper. The samples are stored for representative time periods and at representative environmental conditions (such as temperature and humidity) and then tested to determine whether the internal angle of friction has changed over time.

A material’s permeability also affects flow. Permeability is the degree to which gas (typically air) can pass through the discharging material to fill the void left in the hopper as the material discharges. If the material isn’t permeable, gas can’t enter the hopper, and the material will have a more difficult time discharging. Fine materials can be particularly problematic because there’s very little space for air to move between the particles, which hinders flow.

**Common hopper flow problems**

Bulk solid materials flow from a hopper in either funnel or mass flow, as shown in Figure 2. In funnel flow, material in the center of the hopper flows faster than material at the hopper’s perimeter (Figure 2a) because the hopper angle isn’t steep enough for the material to overcome the friction between the particles and the hopper wall. Hoppers designed using only the angle of slide or repose often exhibit funnel flow. In mass flow, all the material moves down the hopper at nearly the same rate (Figure 2b). This is typically the result of a good hopper design, where the hopper’s cone angle and discharge opening were determined using the wall friction and the material’s internal angle of friction, permeability, and compressibility.

Depending on the material, a funnel-flow hopper can be subject to several common flow problems, including segregation, bridging, ratholing, and flooding. Another common flow problem — vacuum (or suction) — affects both funnel- and mass-flow hoppers.

**Segregation.** Segregation (or separation by size) often becomes an issue with funnel-flow hoppers. As a hopper fills, larger particles tend to roll to the hopper wall and smaller particles remain in the center. This isn’t a problem in a mass-flow hopper because the material at the wall flows from the hopper at the same rate as the material in the center and is remixed as the hopper empties. In a funnel-flow hopper, however, the material in the center moves faster than the material near the hopper wall, so the particle size distribution of the material leaving the hopper will vary with time. Depending on the application, this can affect the quality of your final product.

**Bridging.** Bridging (or plugging), as shown in Figure 3a, is a common problem with funnel-flow hoppers. A bridge is a cohesive arch of material over the hopper’s discharge, resulting in erratic material flow or stopping flow entirely. This leads to costly and frustrating downtime and often to workers banging the outside of the hopper’s cone section with a hammer to break the cohesive arch and restore flow. Bridging is usually caused by an undersized hopper discharge opening, which is why determining your material’s required discharge opening size during testing is important.

**Ratholing.** A rathole, as shown in Figure 3b, is an open channel that develops in the center of the hopper (typically above the discharge opening) through which material flows, while the material around the hopper’s perimeter remains stagnant. Ratholes significantly reduce your hopper’s effective capacity since material flow only occurs in the open channel. Also, the stagnant material surrounding the rathole remains in the hopper as long as the rathole is stable, which can be a problem if your material is subject to time consolidation, degradation, or spoilage.
potentially send tons of material crashing onto the hopper’s cone section, which could lead to a catastrophic failure. Sometimes a collapsing rathole can cause the material to become fluidized. If this fluidization is severe enough, the hopper’s structural integrity can be compromised. When the bulk material becomes fluidized, particles no longer support each other with interparticle friction. The material acts like a liquid, exerting hydrostatic pressure on the hopper walls, which the hopper wasn’t designed to handle. The results can be catastrophic and sometimes fatal.

Flooding. Fluidization can also cause the material to flood uncontrollably from the hopper, as shown in Figure 3c. Flooding can empty an entire hopper in minutes, often taking out feeders, conveyers, and any workers who happen to be standing in the way. To prevent this, you should always use a valve at the hopper discharge — even if a screw feeder is downstream from the hopper. Fluidized material can often easily flow through a screw feeder.

Vacuum. Vacuum isn’t a hopper design flaw as much as an operator issue. If you discharge material from a hopper without adding new material or air to fill the space vacated by the discharged material, a vacuum can develop that can potentially cause the hopper to crush like a giant beer can. A hopper often has vents and valves installed to ensure that such a vacuum doesn’t occur, but it’s usually up to the operator to open the vents or ensure that the vents are interlocked with the hopper discharge. Before operating a hopper, be sure you understand the interlocks and procedures. Crushing a 100-foot-tall hopper is a costly mistake that’s hard to hide.

Mitigating hopper flow problems

A well-designed hopper can provide decades of reliable service, but even the best-designed hopper can experience flow problems. Wear; corrosion; changes to particle density, shape, or size; changes to material permeability or compressibility; or changes to the hopper’s moisture level or temperature can all lead to flow problems even in a well-designed hopper.

If your hopper is experiencing flow problems, such as periodic bridging or ratholing, all is not lost. While banging the hopper with a sledgehammer can be therapeutic and may sometimes temporarily restore material flow, this method is only a short-term solution and can be dangerous. Bridging material can break free suddenly, putting significant force on the hopper’s structure. This can result in the hopper walls splitting open or the cone section completely disconnecting from the rest of the hopper, leading to broken equipment and tons of material flooding dangerously and uncontrollably from the hopper.

Fortunately, there are other ways to mitigate hopper flow problems, often at minimal cost. Flow aids, such as mechanical vibration, aeration ports, or air cannons; special wall coatings; and hopper inserts can help mitigate flow problems without requiring major changes to the hopper, especially if the hopper was well-designed to begin with.

Mechanical vibrators. Mechanical vibrators impart high-speed, low-amplitude vibration to the hopper’s cone section, which fluidizes the material layer against the hopper wall, reducing friction and allowing the material to flow more readily. Vibration, however, can also cause some materials to compact, which makes the material more resistant to flow. If your material can be easily compacted, mechanical vibration may not be the right choice to correct your flow problem.

Aeration ports. Aeration ports can also be added to the hopper’s cone section to inject air along the hopper wall and fluidize the boundary material layer. As with mechanical vibrators, this reduces wall friction and encourages flow. Aeration can be a better approach than vibration for easily compacted materials, but installing aeration ports is a little more complex than installing mechanical vibrators.

Air cannons. Plugging and bridging can also be controlled using air cannons. An air cannon is a pressurized cylinder with a valve that opens into the hopper’s cone section. When the valve opens, compressed air rushes into the hopper’s bottom section, fluidizing the material and breaking up any bridging or plugged material. Air cannons are truly the brute force of flow aids, but they come with issues and must be installed by experts. If the cannon adds too much air, flooding can occur as the fluidized material rushes out of
the hopper’s discharge. Compaction can also be an issue, and the high-pressure air can add a lot of stress to the hopper’s structure.

**Wall coatings.** A less aggressive and more effective method for correcting hopper flow problems is to add a low-friction coating to the hopper wall. Such coatings, which include paint, plasma, electropolishing, and others, reduce the wall friction and can sometimes make a funnel-flow hopper behave like a mass-flow hopper. Low-friction coatings can also reduce wear, erosion, and oxidization to the hopper wall.

**Hopper inserts.** All of the previous mitigation methods work by reducing the frictional force between the material and the hopper wall, but frictional force is just part of the problem. A hopper wall’s frictional effect on material flow is a function of the material’s lateral force against the wall (as characterized by the internal angle of friction). Reducing the material’s lateral force against the hopper wall reduces the wall friction and increases flowability. Mounting an insert in the hopper’s cone section above the discharge opening can help to achieve this. Hopper inserts come in all shapes and sizes, but the most common type is a conical hat shape. The hopper insert absorbs some of the material’s lateral force, reducing the force on the hopper wall. This reduces wall friction and allows a hopper that had previously exhibited funnel flow to achieve mass flow.

There are many experts in this field that can help you design or modify a hopper to ensure adequate material flow. Consult your PBE buyer’s guide for a list of consultants and suppliers.

**References**


**For further reading**

Find more information on this topic in articles listed under “Solids flow” and “Storage” in *Powder and Bulk Engineering*’s article index in the December 2015 issue and in the Article Archive on *PBE*’s website. (All articles in the archive are available for free download to registered users.)

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