Six Steps to Designing a Storage Vessel That Really Works[1]

by
Herman Purutyan,
Brian H. Pittenger
and
Dr. John W. Carson

Designing a storage vessel for your plant requires a methodical approach. This article outlines six steps to follow in designing, installing, and starting up a storage vessel that successfully handles your bulk material under your operating conditions.

Have you experienced delays in starting up a new processing system? Or is your existing or new processing system performing poorly? Often the main culprit is a poorly designed storage vessel – such as a bin, silo, or hopper – somewhere in the system. An improperly designed storage vessel is also more likely to fail structurally than other plant equipment and is more prone to dust explosions or fires and to releasing hazardous emissions. These problems produce unsafe conditions for your workers and the community surrounding your plant.

Factors behind a poor design

What leads to improper vessel design? One cause is considering your vessel design after other system equipment has been selected. Another common mistake is designing the vessel without fully investigating your material's flow properties. Knowing your material's name, bulk density, particle size distribution, and angle of repose just isn't enough.

Relying on your past experience in selecting storage vessels can also lead to a poor vessel design. Why? You typically need a new vessel because your material's characteristics or your operating conditions, or both, have changed.

Designing a vessel based on an inadequate budget that's set before the design process really starts can also result in a poorly functioning vessel. In a project's early stages, the engineer in charge is often expected to quote a cost for the vessel based on as little information as "the

[1] Source: Purutyan, H., B.H. Pittenger, and J.W. Carson: Six Steps to Designing a Storage Vessel that Really Works, *Powder and Bulk Engineering*, November 1999, Vol. 13, No. 11, pp. 56-68. Used with the permission of the publisher.

vessel will be a 14-foot-diameter silo with a cone hopper." Such a simplistic approach can make it hard to go back and increase the budget. So the vessel matching those vague initial specifications can be the vessel you're stuck with in the end.

Steps in properly designing, installing, and starting up a vessel

Avoid vessel performance problems by following a detailed, systematic approach to designing, installing, and starting up your storage vessel. The steps are:

1. Define your operating requirements and conditions.
2. Test your material's flow properties.
3. Develop the vessel's functional design.
4. Develop the vessel's detail design.
5. Fabricate and install the vessel.
6. Start up and maintain the vessel.

Depending on your company's size and whether you're designing a vessel for an existing or new process or for an entirely new plant, the testing, engineering, fabrication, and installation services you need to contract as you follow these steps can vary widely. For instance, if you're adding a vessel to an existing plant, you can hire an independent firm to test your material's flow properties and do functional and detail designs, and then hire a fabricator to build and perhaps install the vessel at your site. If the vessel will be part of a new plant or major plant addition, the engineering consulting firm managing your project may handle the flow property tests and the functional and detail designs and work with a fabricator or vessel supplier to fabricate and install the vessel.

The following sections explain how you can follow each step and avoid pitfalls along the way.

An improperly designed storage vessel is more likely to fail structurally than other plant equipment. When the hopper section in this corn silo failed, falling corn created a vacuum that sucked the silo's top inward.

1. DEFINE YOUR OPERATING REQUIREMENTS AND CONDITIONS

Identify your operating requirements and conditions before you design the storage vessel. Among the most important factors to consider are capacity, discharge rate and frequency, mixture and material uniformity, material friability, pressure and temperature differences, safety and environmental concerns, and construction materials. Your application may require you to consider other factors as well.

Capacity

First consider your storage vessel's required capacity. For help in setting this capacity, look at your plant's business or operating strategies. For instance, a growing trend in many plants is to reduce raw material inventories to free up working capital. If this is the case in your plant, your storage vessel may require a relatively small capacity.

If the storage vessel will be at your process's front end, the vessel capacity may be dictated by the raw material's delivery schedule, shipping container type and size, and usage rate. For instance, if your plant receives one truckload of material per day, one relatively small silo may be enough. But if a larger quantity is delivered by train or ship once a month, you may need a much larger vessel (or multiple vessels) to store it.

If your vessel will be located at an intermediate process step, base the vessel's capacity on your process requirements. For instance, the vessel may need to hold enough material to prevent shutting down a furnace or reactor when an upstream problem temporarily halts material flow. Or you may need to base the vessel capacity on the quantity needed to even out differences in the rates of two process steps.

If your vessel is located at the process's back end, base the vessel capacity on your plant's shipping schedule, product orders or sales cycles, shipping container type and size, and your plant's business strategies (such as a just-in-time shipping policy).

Discharge rate

Regardless of where your storage vessel is located, it must deliver material to a downstream process at a required rate. You need to specify the required discharge rate early in the design process and communicate it clearly to the project engineer. For instance, are you stating the discharge rate as an average rate? How did you determine it? Is it based on volume (such as cubic feet per hour) or mass (such as pounds per hour)? Be specific: If your downstream process requires 10 t/h of material but the vessel will discharge material only four times per hour for 5 minutes at a time, the *instantaneous discharge rate* the vessel must provide is 30 t/h. A vessel that can discharge material at only 10 t/h won't be able to deliver enough material to your process in those four 5-minute periods.

Also consider the minimum and maximum discharge rates your vessel must provide in both normal and upset conditions. Some processes are much more sensitive to discharge rate variations than others. For instance, such variations may not be important if your process transfers a certain-size batch after a given time. But if your process combines multiple material streams, each from a different vessel, into one mixture, each vessel must have a uniform discharge rate to maintain the proper proportion of ingredients in the mixture.

Discharge frequency

Specify the vessel's discharge frequency early in the design process. When a material is stored over time, some of its flow properties can change. Ensure that your vessel is designed to handle these changes by considering how long your material will be stored in the vessel between discharges. Will your vessel be used in a one-shift-per-day operation that leaves material at rest in the vessel overnight? Will your process shut down for weekends, leaving some material in the vessel? During planned shutdowns, will you empty the vessel or will you leave material in it? How long will material remain in the vessel during a shutdown – 1 week? Longer?

Mixture and material uniformity

If your vessel will hold a mixture consisting of several ingredients, your process may require that the mixture remain uniformly mixed during storage and discharge. If your vessel stores ingredients for a dry salad dressing mix, for instance, it should discharge all ingredients together in the right proportions rather than herbs first, seasonings next, and croutons last. If your vessel stores dry ingredients for cement, it should discharge the limestone and clay together rather than one after the other to your mill.

If the storage vessel will be at your process's front end, the vessel capacity may be dictated by the raw material's delivery schedule, shipping container type and size, and usage rate.

If your vessel will store only one material, you still may need to be concerned about maintaining the material's particle size uniformity during storage and discharge. Coarse and fine particles with the same chemical content can perform quite differently. If your downstream process is designed to handle a wide particle size range, design the vessel to prevent the discharge of only all fines or all coarse.

Off-spec material or dust that's returned from the process to your vessel can also affect the material's uniformity. Early in the design process, consider whether off-spec material or dust must be returned to your vessel and how it can be returned to prevent affecting the material's uniformity.

Material friability

If your material is friable, a poorly designed vessel will degrade it. For instance, detergent agglomerates can break up during vessel loading and discharge, compromising the final product's quality. Attrition of pasta or cereal flakes during loading and discharge can result in scrapped product.

Pressure and temperature differences

Your material can behave differently depending on the gas pressure and temperature it's exposed to. Identify the gas pressure in equipment upstream and downstream from your vessel. If these differ from the pressure inside the storage vessel, they can affect your material's flow properties. The same is true if your process operating temperature is different than the temperature inside the storage vessel. Determine the temperature conditions, including minimum and maximum ambient temperatures (especially for outdoor storage) and minimum and maximum incoming material temperatures, that can affect your material's behavior so the vessel you design can handle these conditions.

Safety and environmental concerns

Determine whether your material is likely to explode or burn. For instance, materials such as coal and grain generate flammable or ignitable dust. Others such as polyethylene and polypropylene can contain volatiles. Use this information to design the vessel with adequate explosion- and fire-protection features (such as an explosion vent or explosion-suppression system) or to decide whether to use an inert gas (such as nitrogen) in the vessel.

Consider whether material spilled from the vessel or fugitive dust or fumes released from it can injure your workers or pollute the environment. Also determine whether contaminants, atmospheric gases, humidity, and temperature can adversely affect the material stored in your vessel. In either case, design the vessel to safely handle these conditions.

Construction materials

Your material's chemical composition and other properties can limit the choice of construction materials for your vessel. An abrasive material can wear some wall materials. A material containing a corrosive substance such as a salt or acid may require a vessel with epoxy-coated walls. Residue from previous materials in upstream equipment can also affect the walls.

For instance, an acid not completely removed during equipment washdown may linger in upstream process equipment, travel with your material into the vessel, and corrode the walls.

2. TEST YOUR MATERIAL'S FLOW PROPERTIES

Testing to identify your material's flow properties is critical to successfully designing your storage vessel. Run tests on a representative sample of your material under conditions that match the worst-case conditions you expect the material to be handled in. For instance, if you expect your material to degrade during pneumatic conveying into the vessel, test a sample of material that's been pneumatically conveyed under the same conditions. [1]

You also need to test the material's flow properties under the conditions that will be present in your vessel. When possible, obtain samples from your vessel supplier of the wall materials you're considering so you can test the bulk material's behavior when flowing along these surfaces.

Also get samples of your bulk material from the material supplier you'll use rather than another supplier. Materials with the same chemical composition from different suppliers can have quite different flow properties. If the particle size, shape, moisture content, or other properties of the sample differ from those of your actual material, the test results won't be of much help in designing your vessel.

If you can't obtain a sample of your material because it hasn't been produced yet, you may be able to test a sample from a pilot plant. Although your production-grade material may be different than this sample, testing the pilot plant sample can help you at least establish a baseline for designing the vessel.

Vessel diameter can be limited by the space available in your plant or the vessel's construction method.

If you can't get a material sample because you haven't yet identified a supplier for it, you can obtain a range of flow property data for the material from others who have conducted flow property tests. For instance, to design a silo that will receive coal from many locations around the world, you can survey flow properties of coal from diverse locations to at least identify some vessel design basics. While clearly less accurate than testing the actual coal samples, using this method is better than making your decision without any coal data.

If your vessel will hold materials from several sources or hold several grades of one material, run a series of tests on samples of each material or grade. The tests can identify which samples have extreme flow properties that will affect your vessel design.

Before running tests, consider which flow properties you need to identify for designing your vessel. Distinguish between tests that provide qualitative, relative data and tests that provide quantitative, absolute data. For instance, tests for angle of repose, flow time through a funnel, and compaction ratios will generate qualitative, relative data that, at best, may help you find differences between samples but won't help you design the vessel.

Instead, use quantitative, absolute tests that identify flow properties important to vessel design. These include tests of the material's

[1] Find more information on how to conduct flow property tests in articles listed under "Solids flow" in *Powder and Bulk Engineering's* comprehensive "Index to articles" (in the December 1998 issue and on *PBE's* Web site, www.powderbulk.com).

cohesive (shear) strength, compressibility and permeability, segregation tendencies, and abrasiveness. Wall friction (friction between the material and vessel wall) is another important test. For most of these tests, you can use the Jenike Shear Tester, adopted as the only standard flow property test device by the American Society for Testing and Materials (ASTM), International Standards Organization (ISO), and European Federation of Chemical Engineering.

Conduct the tests under the conditions in your process that are most likely to adversely affect your material's flow. For instance, a material generally becomes harder to handle as temperature increases (although freezing can also make a material harder to handle). Increasing the material's moisture content, increasing it's storage time at rest, and decreasing its particle size also can cause flow problems. So run your tests with materials at the maximum temperature and moisture and after the maximum storage time at rest that you expect in your process. If your material has a wide particle size range with a significant portion (15 to 20 percent or more) of particles less than 1/4 inch, conduct the flow tests on these fine particles only.

3. DEVELOP THE VESSEL'S FUNCTIONAL DESIGN

Consider your operating requirements and conditions and the material's flow properties to develop your vessel's *functional design*. This functional design specifies the features the vessel needs to function effectively in your application. The vessel features that will be designed during this step include:

- Cylinder height, diameter, and construction material.
- Hopper shape, slope, and construction material.
- Outlet size.
- Feeder type and size (including details for activating the entire outlet, if necessary).

Optional features that you can also determine at this step include:

- Discharge valve type (slide gate, butterfly, and so on) and size.
- Hopper insert or flow aid type, location, size, and construction material.

To determine the vessel's maximum diameter and height, consider your site conditions and construction factors. Vessel diameter can be limited by the space available in your plant or the vessel's construction method. For instance, a vessel that will be fabricated in a supplier's shop probably can't exceed 14 feet in diameter to be transported in one piece to your site. Vessel height can be limited by your surrounding structure's height, your area's seismic or wind-loading conditions, the amount of associated process equipment that must be located above or near the vessel, on-site construction factors (such as crane size), or the vessel foundation design (which can be limited by the area's soil conditions). These limitations can also determine whether you need to install one or more vessels.

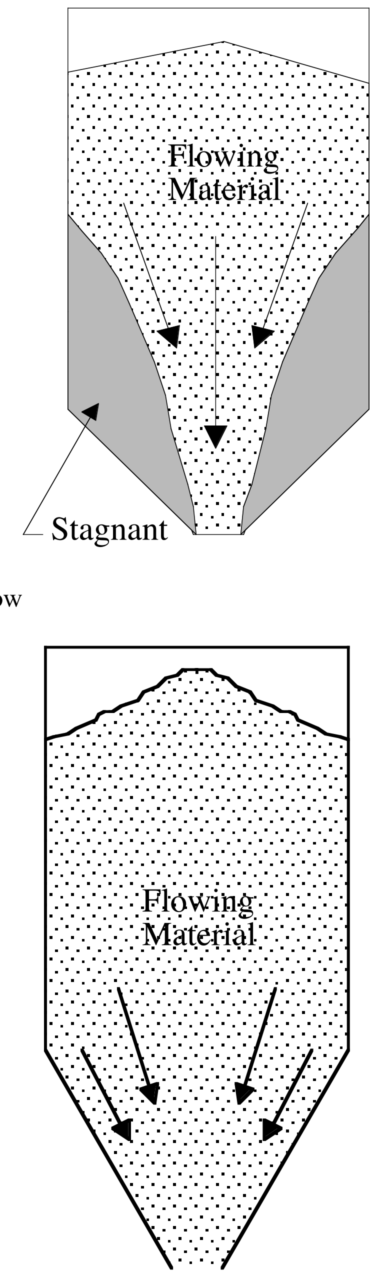
The key factor to consider in selecting the vessel's other functional design features is the appropriate flow pattern inside the vessel. Several vessel features – including the outlet size, cylinder and hopper shapes, hopper wall slope, hopper surface material, feeder (located at the outlet), and any required valves, hopper inserts, or flow aids – affect the flow pattern.

The two primary flow patterns in a vessel are *funnel flow* and *mass flow*, as shown in Figure 1. In funnel flow (Figure 1a), an active flow channel forms above the outlet with nonflowing material around the vessel periphery. The result

Fig. 1: Flow Patterns

a. Funnel Flow

b. Mass Flow



is a first-in last-out flow sequence, with potential caking of stagnant material and sifting segregation in which fines typically exit first. This produces uneven discharge with inconsistent bulk density and uncontrolled flow. As the material level in the vessel drops, layers of the nonflowing material may or may not slide into the following channel. This can produce a stable rathole in the vessel, where material outside the channel remains stagnant.

In mass flow (Figure 1b), all the material is in motion whenever any is withdrawn from the vessel. Material from both the vessel center and periphery moves toward the outlet. This provides a first-in first-out flow sequence, eliminates stagnant material, reduces sifting segregation, and provides a steady discharge with consistent bulk density and uniform, well-controlled flow.

Despite the advantages of mass flow, it isn't always possible, practical, or cost-effective to install a vessel that provides it. In fact, a vessel that provides funnel flow can be acceptable for some applications. For instance, you can use a funnel-flow vessel if your material is free-flowing and coarse enough to prevent aeration and if your process won't be affected by mixture segregation, particle size segregation, or first-in, last-out flow.

But when these conditions aren't acceptable, your vessel must provide a mass-flow pattern. Achieving mass flow requires a vessel outlet that's large enough to prevent material from arching (also called bridging) over the outlet, hopper walls that are smooth and steep enough to promote material flow at the walls, and an outlet that's entirely active (which requires choosing a feeder that allows this).

The minimum outlet size that can overcome arching is directly related to your material's cohesive strength. Use the cohesive strength test results you obtained in step 2 to calculate a minimum outlet size. Also consider whether a circular or elongated outlet is better for your application.

Your required discharge rate also affects the outlet size. If the material – particularly a fine powder – deaerates in the vessel, the discharge rate can slow greatly. Use the permeability test results from step 2 to calculate your material's discharge rate for various outlet sizes.

The shape, slope, and construction materials of surfaces in contact with your material also affect the flow pattern. How cohesive and frictional your material is determines what hopper geometry – cone, wedge, transition, or other – your vessel will have. Because a cone hopper must be 10 to 12 degrees steeper than a wedge or transition hopper of the same construction material, the wedge or transition hopper may be more appropriate if you have limited headroom. The outlet width in the wedge or transition hopper can also be equal to one-half the cone hopper's outlet diameter while having the same effect in preventing arching, so if your material's cohesive strength would require a large circular outlet, using a wedge or transition outlet may work fine and also save headroom.

Selecting the proper feeder for the vessel outlet is also important because mass flow can't occur if the feeder can't withdraw material from the entire outlet. A lip, ledge, partially open gate, or mismatched flange at the outlet can also be fatal to mass flow.

To choose a feeder, consider whether your material is fine or fluidizable. Most dry solids feeders can't hold back fluids. For instance, a screw feeder can't contain a fluidized material, so if the material in the vessel never settles during filling or becomes fluidized, it will flood out of the feeder.

If your vessel will have a unique design and you don't know all your operating conditions or material flow properties, you can test the vessel and feeder design in a scale model. However, you need to understand which of your material's flow properties can be scaled down, because not all of them can. For instance, wall friction results can be scaled down, but the results for the minimum outlet size to overcome arching can't.

4. DEVELOP THE VESSEL'S DETAIL DESIGN

Developing your vessel's *detail design* requires selecting its construction materials, fabrication and installation methods, and structural design. Once the detail design is completed, your design engineer can generate engineering drawings of the vessel. The drawings will be used to fabricate the vessel and in many cases are given to firms submitting bids for the vessel fabrication. To ensure that all relevant functional design details from step 3 are properly incorporated into the detail design, you must communicate all functional design points from step 3 to the engineer.

For instance, your functional design may specify a Type 304 stainless steel hopper surface with a number 2B finish, but if you don't communicate *all* the details clearly, the engineer may interpret this specification as simply a Type 304 stainless steel hopper surface. This means you may end up with a surface fabricated from mill finish or number 1 finish Type 304 stainless steel, which is much more frictional than a number 2B finish surface and will cause flow problems.

Determining how to fabricate your vessel is one of the first things to consider in the detail design. The three most common fabrication options are reinforced concrete, welded steel or aluminum, and bolted steel or aluminum.

A reinforced concrete vessel is typically used for large-capacity applications. It typically has a 35-foot or larger diameter and a total volume greater than 30,000 cubic feet. The vessel is often fabricated in a bank or group of multiple vessels. A welded steel or aluminum vessel can be of various sizes and fabricated in the shop or at your site. Shop fabrication, which provides close control of the welding process, is an option only for a vessel with a diameter of 14 feet or less. This fabrication method also allows a special vessel coating such as epoxy to be applied (and cured, if necessary) before the vessel is shipped. A bolted steel vessel can have a 100-foot or greater diameter and consists of shop-fabricated (and, sometimes, shop-coated) pieces assembled in the field.

To select a fabrication method, consider the construction material and surface coating or lining you need, the cost and installation (or shipment) method for each type of fabrication, and the service life of vessels fabricated by each method.

Also consider your vessel's installation requirements in the detail design. If your vessel will be in a hard-to-access area and you have a limited amount of downtime to install the vessel, it may have to be designed and built in sections. For instance, designing a vessel with a hopper in multiple sections may eliminate having to move walls, other equipment, pipes, and electrical components in your plant and reduce the vessel's installation time. While the hopper's cost will be more than that of a one-piece unit, the overall project's cost can be reduced because installing the vessel in sections will require less downtime.

You need to determine the vessel's structural design, too. This requires calculating the pressures that your material will apply to the vessel walls. The pressures depend on the material's flow properties, the vessel flow pattern, and the vessel geometry. Various codes, including those of the American Concrete Institute (ACI) and American Society of Agricultural Engineers (ASAE), address aspects of structural design and vessel construction, but none covers all the conditions you must consider.

Carefully consider how to add such items as access doors, poke holes, flow aids, and level sensors to the vessel. If you place them poorly, they can cause flow problems. For instance, an aeration pad installed on the hopper surface to prevent potential flow problems may actually create them. To avoid this situation, have the engineering drawings reviewed by the individuals who specified the vessel's operating requirements, determined your material's flow properties, and prepared the functional design.

5. FABRICATE AND INSTALL THE VESSEL

Before and during fabrication, you need to ensure that the vessel fabricator correctly interprets the detail design as well as understands the basis for the design. Otherwise, the fabricator can make a mistake, such as trying to improve your vessel's number 2B finish by polishing it, unaware that polishing this surface often increases wall friction and can stop the material flow in your vessel. Other details, such as a slightly oversized flange, can also appear to be trivial to the fabricator, who may make the flange smaller so it fits the vessel outlet better. The result can be a flow stoppage.

Before installation, inspect the vessel against the detail design to ensure that the vessel meets your design specs and intent. It's easier to fix problems now than after the vessel is installed.

In mass flow, all the material is in motion whenever any is withdrawn from the vessel.

At installation, which can be handled by a vessel supplier, an engineering contractor, or your plant staff, ensure that the hopper's sloping walls – where wall friction is critical – are protected. If the vessel requires field welding, those surfaces should be draped with fireproof cloth to prevent weld spatter from marring them. Minimize any welding on the sloping surface, and vertically orient welds so they follow the direction of material flow.

Sometimes a shop-fabricated vessel is shipped with a protective coating. Before you load material into such a vessel, remove the coating and restore the surface to its original condition. It's a common misconception that material flow will remove the coating and expose the underlying surface. In fact, if the coating is more frictional than the wall surface, no flow will occur at the walls and the coating will remain. Once you've loaded material into your vessel, the only way to remedy this problem is to unload the vessel (now a real problem) and clean the walls.

You can have similar problems if you load your vessel with a material other than the one the vessel was designed for. Sometimes this is done in early flow trials to "work out the vessel's bugs" - but the bugs that result can be entirely different from those produced by your design and material. If you use a different material for flow trials, use one with flow properties similar to those of your design material.

Loading your vessel with a material produced during a process startup can also produce problems. The startup material often has substantially different moisture content, particle size, chemical composition, and even surface structure, and it won't give accurate results in your flow trials.

6. START UP AND MAINTAIN THE VESSEL

After installation, those who installed the vessel should be present at startup. You may also want the engineer who handled the vessel's detail design to be present. Startup involves loading the vessel with your material and checking that the material discharges as required from the outlet.

After startup, routinely inspect your vessel to prevent small problems from growing into large ones. Inspect the hopper's sloping surfaces for any changes in condition, such as liner or coating wear, that can produce flow problems. Inspect the vessel walls for thin spots caused by wear and corrosion, especially around the cylinder-hopper interface and near the outlet. This can help you circumvent serious structural problems. Inspect the welds and support structure to identify any deterioration that needs repair. Routinely inspect the vessel's relief valves to prevent overpressurizing the vessel, and inspect related dust collection filters, feeder gaskets, and seals.[2]

If you decide to store a different material in your vessel, be sure to consider more than just the material's bulk density. If the material's flow properties are different from those of your original material, the flow pattern through the vessel can be different and impose different stresses on the vessel. This can cause a vessel wall section not designed to handle high stress to experience loads exceeding the sections design limits, resulting in vessel failure. Before placing a different material in your vessel, measure the material's flow properties and review your vessel design in light of these properties.

SOME FINAL ADVICE

While it's impossible to cover all the details of designing a storage vessel for reliable operation

[2] See "How to prevent silo failure with routine inspections and proper repairs," by Dr. John W. Carson and Richard T. Jenkyn in *Powder and Bulk Engineering,* January 1990, pages 18-25.

in one article, the six steps described here provide a good road map for starting this journey. Work with experts – whether they're from your firm or are independent engineers or consultants – to carefully consider the details of your application. Making the design project a top priority and directing the appropriate resources toward it can help you design a vessel that performs reliably and safely.