Methods for Design of Hoppers. Silos, Bins and Bunkers for Reliable Gravity Flow, for Pharmaceutical, Food, Mineral and Other Applications

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SYNOPSIS

It is now four and a half decades since Andrew Jenike introduced the first integrated method for characterising powders for flow, and using this information to design a hopper that would discharge without hang-up. Sadly, many users and designers of hoppers still do not benefit from this, so a lot of process vessels in industry still suffer from rat-holing, arching and bridging. Objections of cost, time and questionable accuracy were levelled at the original hopper design method, in spite of the breakthrough it represented. However, over the last 40 years these problems have been overcome with the introduction of faster, easier to use and more sensitive powder flowability measurement techniques, and a lot of experience of what measurements matter with which materials and in what operational scenarios.

This paper will pull together various lessons learned from many years of hopper and silo design projects, and show a practical approach to deciding (i) what flow pattern is required (mass flow or core flow), (ii) what measurements need to be made of the powder properties, and (iii) what design models should be used, based on the material being handled and the operational requirements of any given case.

INTRODUCTION

The problem – unreliable or irregular flow

Unlike liquids, powders support shear stress when at rest. Many powders and bulk solids also have a property known as “cohesion” which means that after they have been subjected to pressure, they can retain increased strength. This is easily illustrated by picking up a handful of the material and squeezing it, if it is not “free flowing” it remains in a ball when you open your hand.

Such powders can form an “arch” or “rat-hole” inside a vessel, preventing discharge and requiring the action of hammering, vibration, aeration or other methods to promote flow. Examples of the effect of this problem are shown below.

Fig. 1 Moist powdered talc consolidated in a badly designed feed hopper. The operator cleared this by rodding with a broom handle, and when this jammed in the screw it was ejected past him like a javelin!

As a result, many hoppers on plants of all sizes and in all industries suffer from damage from hammering, popularly known as "hammer rash". The flow interruptions give rise to production difficulties, and the hammering itself requires operators to divert from their other tasks; it commonly leads to safety issues with noise, hand injuries and back strain.

Fig. 2 "Hammer rash" on bins with flow problems – the effects on the bins are obvious, but how much damage has this done to the operators?

Avoiding the problem

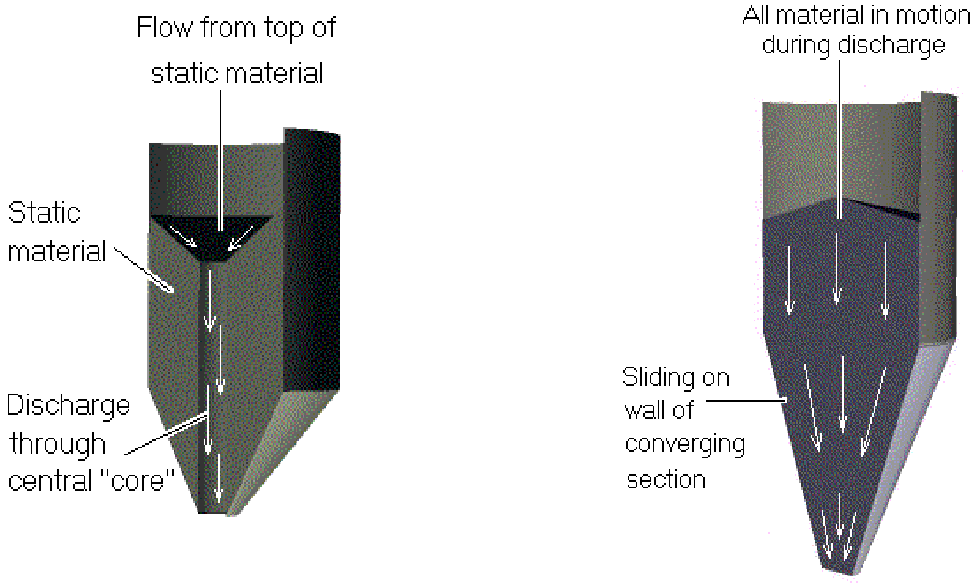
The first rational method for design of gravity mass-flow hoppers was published by Jenike in an accessible form in 1964[1]. As such it was the first method put in the public domain that allowed a designer of a silo or hopper to choose the geometry of the bin (specifically the hopper angle and the outlet size) on a rational basis, based on measurement of the flow properties of the bulk solid to be discharged.

Others followed (e.g. Walker[2]), and since then, many re-publications, slight variations, and various improvements and refinements have been published[3],[4],[5] but the underlying method has been found to be sound and reliable and endures in use to this day. Many studies have shown the value of the method for arriving at hopper and silo designs that work reliably[6,7].

OVERVIEW OF RATIONAL METHODS FOR HOPPER DESIGN

Mass flow and core flow

One of the first points to understand is that two principal flow patterns occur in a hopper or silo, no matter how small or large:-



a) Core flow discharge *b) Mass flow discharge*

Fig 3 Patterns of discharge from hoppers

There are various advantages and disadvantages of each flow pattern, again well described in standard texts.

Principle of the rational design method

The rational method for hopper design is based on a model of stress distribution in the hopper, informed by measurements of the flow properties of the material being handled, that predicts the flow pattern that will occur and whether or not flow will be reliable. The details can be found in any standard text of powder technology so will not be repeated here. Though difficult to derive, it is easy to use.

The key point to understand is that if you wish to use the method, you need to get a sample of the powder(s) that will go through the plant, and undertake some measurements of the flow properties. It recognizes that every different powder is unique in its flow properties, which is a fundamental trait of bulk solids.

Development of the art

Several groups around the world have been founded on providing analytical and design services for bulk solids handling systems, using the Jenike gravity mass-flow design method for at least part of their work, and these groups have designed (and redesigned) thousands of hoppers and silos for materials that might be regarded as "difficult", in other words materials that would not discharge reliably from vessels built to any design that had not been derived from such a "rational" approach. It is fair to say that as a design approach, it is virtually failure-free; the experience of the author's group is that provided the material tested is representative of that loaded into the plant, and any issues of change in moisture content, time in static residence, caking effects etc. are taken into account, it delivers a hopper design that can be guaranteed to work.

One of the objections to the use of any rational hopper design method has historically been the high cost of undertaking the characterisation tests. Particularly when using Jenike's own design of shear cell, it can be two days' work by a highly skilled technician to undertake the measurement of one sample of bulk solid and process the data to arrive at the hopper geometry. Then if the hopper has to discharge a range of materials, or materials with a range of moisture contents etc., all this had to be repeated several times. This adds up to a lot of cost and especially for small vessels, can easily outstrip the cost of making the hopper many times over!

The other difficulty with the Jenike cell was that it could operate only at relatively high stresses, so when designing small vessels this led to massive over-specification of the outlet size needed for reliable flow.

Walker's introduction of an annular shear cell for powder testing[8] can be seen in the context of history as a massive step forwards in the characterisation process. Walker's cell could do the job in a third of the time and with much less scatter in the results, even with less skilled operators. It did not overcome the limitation of working at high stresses though. Sadly, Walker's cell did not find many users, but it led to the development of better annular shear testers, in particular the Peschl and Schulze annular shear testers, and more recently the Brookfield Powder Flowability Tester, the first fully-robotised powder shear tester that integrates testing and analytical functions in embedded software and produces data for hopper design in a much shorter time at lower cost.

Fig. 4

The latest annular shear tester for powders and bulk solids, known as the Brookfield PFT

Current state of the art and width of deployment

Using the latest shear testers, it is economic to take a variety of different samples of materials that will go through a plant, test them thoroughly including the effects of moisture content, size distribution variation, static residence and other plant or material variables, in a short time and at moderate cost, to come to a hopper design that will work reliably. This is equally applicable to micro-dosing machines, tableting facilities, small feeders and powder processing machinery as well as bulk hoppers and large silos.

More and more suppliers of solids handling equipment are using the technique; in the UK, the number of equipment manufacturers incorporating the latest material characterisation and hopper design technique in to their design roadmaps has gone up by a factor of four in the last five years; they still remain in a minority, but definitely a growing one.

THE ALTERNATIVE

Many equipment manufacturers still do not use any rational method to choose their hopper designs. Instead they rely on past experience with material that had the same name ("this silo shaped worked on this material the last time, so we'll use it again"), or guesswork based on the principle that a "standard" hopper geometry will be supplied and once the equipment gets on site, vibrators and/or fluidisation pads will be added to persuade flow to occur. This drives a vast after-market in supply of flow promoting devices, especially vibrators, "knockers", aeration devices, air cannons and so on. Even so it is still very common to see hoppers with "hammer rash" due to operators reverting to the basic method of hammering.

Overall, it is very disappointing to those that promote excellence in bulk solids handling system design, to see that the up-take of the rational method for hopper design has been so slow, especially given that it has been proven to be so successful over so many years.

The reasons for the slow up-take are various:

- Until recent years, the cost and the skill requirement of undertaking the powder measurements have been rather high and the timescale rather slow. This is a problem especially when the equipment manufacturer knows he is one of several bidding for the job, and the time invested in the design stage is at his own expense!
- Most of the engineers designing solids handling equipment do not have any formal education in the area, because it is generally ignored as an academic subject in most college and university courses. Only a handful of universities around the world offer a course in bulk solids handling, even though most manufactured goods incorporate powders. Consequently, most engineers working in this area remain unaware that there is a sound method available for hopper design.
- Most buyers of solids handling equipment are equally unaware of the benefits of good design, looking only for lowest cost. In this environment, any additional cost at the design stage makes the supplier's bid harder to sell, as he is more likely to be under-cut by someone else who is unaware of the need for good design practice and willing to take the risks in not undertaking powder measurements and hopper design work!

- A hopper customised to the needs of the powder will always cost a little more to make than one to a standard design, and again unless the buyer is well aware of the advantage of making this small investment, the cheaper offer will win.
- Many hoppers, silos and feeders in industry discharge with sufficient reliability although no rational method was used to define their geometry – they are built to the supplier's "standard" design, and if there is a problem on site they have added vibrators, aeration pads etc to get flow. Many times, people get away with this "bodging" approach.

HOW TO DECIDE ON A HOPPER DESIGN PROCEDURE

We need a method to decide, given a certain project, whether or not we need to use a rational method of hopper design and when we can get away with "short-cut" methods. There are two basic groups of variables that affect this decision. One might be described as material variables, the other as process variables.

Material variables

There is no doubt that the greatest key to success in sourcing or designing any solids handling equipment is to know the behavior of the material that will be going through the equipment, so you can decide what will work for it.

Flow properties are one of the most important things to have knowledge of. Most importantly, is the material "free flowing"? How do we know this? One way is to pick the material up in your hand and squeeze it. If it forms a ball when you open your hand, it is cohesive. If not, i.e. if it still drops through your fingers like dry sand, then it is free flowing. But is it likely to remain always the same? Many materials have variability in them, due to changes in moisture content, size distribution and source of supply. You need to look at this.

In addition to flow properties, you need to know something about the tendency of the material to "time consolidate" and to "cake". Time consolidation is where a material gains strength when it is left under pressure e.g. at the bottom of a storage vessel for a period of time. Most cohesive materials will time consolidate, but the rate of time consolidation varies enormously – something soft like a detergent powder can easily double its strength when left not moving for as little as three hours; cement powder will gain perhaps ten to twenty percent in strength after a few weeks. Fly ash can fall anywhere between these extremes depending on its composition, and different pharmaceutical and food powders can be anywhere along the range. Some free flowing materials, if you leave them under pressure in a vessel, can also time consolidate.

"Caking" is a much higher increase in strength that occurs not just because of settlement of the particles, but when the particles weld together to make a very hard structure. This can happen for a variety of reasons. Sugar cakes due to temperature changes, going as hard as rock! Feed pellets can cake due to fermentation in long term storage. You need to know if your material can do this, in the timescale between the vessel being emptied out completely.
Segregation is a very common problem in blended materials. It also affects materials that have a broad size distribution (in practice this means most materials except dust-free pellets!). There are two main sorts of segregation, **free surface segregation** that happens to free flowing powders and bulk solids (especially coarse ones), wherein the larger particles roll

easier down an angle of repose slope and **air-induced segregation** that happens to powders that contain fine particles as well as coarse, wherein fine particles settle more slowly in air so tend to get held back in a chute or from settling in the receiver of a pneumatic conveyor. If your material is capable of segregation, it affects the choice of hopper design, which in turn affects whether or not you need to use a rational hopper design approach.

Sources of information on material behaviour

Knowing the material from experience

Have you designed equipment for the same material before? But before you answer "yes", ask yourself this question; "Is this material really the same as the one I handled before with the same name?" Is it from a different source of supply, or could it have a different moisture content, particle size distribution, small changes in ingredients etc? Be especially wary of materials that have the same name, and are to the same specification, but behave differently. If you are confident it is the same, you can probably get way with the approach you used before, as long as you are not stepping outside the bounds of the process variables you used before. For example, a simple core flow vessel might discharge the material, but if you need an accurate metering of the powder the bulk density might be too variable in core flow so you may need mass flow. So beware of using experience to decide on a vessel design – look carefully at both the material and the process variables.

Characterisation

The best way to know about the material behavior is through a characterisation study. Unfortunately it is also the most expensive and takes the longest time. Ideally you would measure all the possible relevant properties, i.e. flow properties, caking tendencies, segregation tendencies etc. but in reality, a more limited programme may be adequate. Requirements for a sensible programme of characterisation depend on both process variables and material variables, and will be discussed below.

Reference from other sources

It may be possible to get useful information from the plant that currently handles the powder, or from colleagues that have designed plants for the material. But again beware of the fact that the powder might be different, and also that there may be differences in process variables from what you are designing. Just because a plant doesn't have any problems with flow of a particular powder doesn't mean that the powder has no flow problems – it may be just that they are using equipment especially well suited to the powder! So when collating experiences from others, be cautious of the process conditions as well as the material itself.

Never rely on published sources for material flow behavior. For example, some silo design codes give example values for powder properties for structural design. Never use these for flow design, because there is no knowing what the precise specifications of the materials of any given name were, or what techniques were used for their measurement.

Process variables

The main process variables include the quantity of material to be stored and the discharge rate required. However, if the vessel is part of a feeding system it is also important to know the accuracy of feed rate required; this is usually given as a percentage, but it can still be misleading. Over what time base is this accuracy is to be measured? Is it a percentage of the actual rate/quantity being weighed, or a percentage of the maximum throughput/quantity being weighed? What are the largest and smallest quantities or rates to be weighed?

Equally important is whether there is some process requirement that determines whether first-in-first-out discharge is required (for example to allow the material a consistent residence time for cooling or ageing).

Time between discharges is important with any materials that are subject to caking or time consolidation. There are two considerations – how long will the material be left static between taking some out and taking the next lot out (this is important for mass flow hopper design) and how long between successive complete emptying-out of the vessel (more important for core flow design).

Another important process variable is whether you care about segregation. Many materials have a natural tendency to separate into fine and coarse fractions, which may cause deblending if it is a blended material, or cause other problems due to change in particle size. Not all materials do this; and there are various means for overcoming it. But from a process viewpoint, it is important to consider whether segregation would matter to you, if it did occur.

Deciding on the flow pattern in the vessel

One of the most important things to decide is whether you want mass flow in the vessel, or whether core flow will do. In some cases it doesn't matter, but in many cases it is absolutely critical to correct operation. In any event, this should never be left to chance – always make a positive decision on which one you prefer.

There are three main reasons why you might want to use mass flow.

1. The material is cohesive, ie not free flowing; the outlet size you need for reliable discharge in mass flow is much smaller than core flow, saving you money on the feeder.
2. The material can change with time – e.g. it can settle and "time consolidate", it is subject to biological action or fermentation in long term storage, it can cake under pressure and with temperature change. Then, mass flow minimizes the storage time in static residence, overcoming these problems.
3. The material tends to segregate, and you are bothered about this; make materials, especially coarse, free flowing materials, tend to separate when they fall on the cone of material inside a hopper as you fill it. Coarse goes to the walls and fine to the centre (or the reverse if it is loaded pneumatically). Mass flow helps to recombine the separated material at the outlet.

If any of scenarios 2 or 3 above apply, you should choose mass flow, and a rational design method should always be used. If only scenario 1 above applies, then core flow might still be suitable but it depends on the flow properties of the material – and when you are designing a core flow hopper for a cohesive material, you should use a rational design method.

If none of the above considerations apply, then core flow may be preferable. Core flow has several advantages:

1. The sides of the hopper don't need to be so steep, so you get a lower vessel (or more storage in a given head-room).
2. The material doesn't flow on the cone of the hopper so it minimizes wear of the vessel if you are handling an abrasive material
3. Much less characterisation and design work is needed, if for a free flowing material.

<u>**"THE RULES"**</u>

Summarising, a set of "rules of thumb" can be expressed to decide on what characterisation and hopper design procedure to use

- If a material is free flowing and is always going to remain so (no danger of increased moisture, time consolidation or caking effects) then from a purely flow perspective, core flow is adequate and there is little need to use a rational hopper design procedure such as Jenike. The exception to this rule is if the material is capable of segregating, and if you care about it; if segregation doesn't matter to you, again core flow, with no special attention to hopper design for flow, is adequate.

- If your material can segregate and this bothers you, then you may need to use mass flow. But if the material is always free flowing, with no tendency to time consolidate or cake, the only measurement you need is a wall friction test to get the angle needed for mass flow. The hopper outlet size can be chosen to suite the process below. A wall friction test is a very simple, cheap and easy test to do so there is no excuse for not doing it, if these conditions indicate it is required!

- If the material is free flowing, but there is a danger of it spoiling with time e.g. going hard, fermenting or caking, then core flow (with little requirement for a special hopper design procedure) will be fine as long as the vessel is completely emptied frequently enough, before the spoilage can happen.

- If an accurate dosing of powder is required, either as a rate of a quantity, then using mass flow based on powder characterisation will always help as it gives a more consistent bulk density at the feeder – whether the material is free flowing or cohesive.

- The biggest challenge comes with a cohesive material. If you can find relevant experience you can rely on, and you are working within the same process variables, then you can get away with using the same hopper design as was used before. But if you don't know the material really well, or you are moving into new processing conditions, then really you should undertake some characterisation work – at least Flow Function, Wall Friction and Bulk Density – and use a rational hopper design procedure to determine what geometry is required for reliable flow. The procedure will tell you about geometries for both core flow and mass flow. Take account of time consolidation, and if you decide on core flow, again beware of segregation.

- Another alternative, and quite popular, design philosophy for fine powders is to promote discharge using aeration. Provided the powder is not too cohesive, and as long as it does not suffer substantial time consolidation, then it is usually possible to use a "standard" hopper design (i.e. a shape arrived at by convenience and not via a rational hopper design procedure – that would not provide reliable flow by itself) and add aeration strategically to promote flow. The biggest problem, if you are going down this route, is that there is no sure way of knowing exactly what powder cohesion level is "too cohesive", or indeed how much air flow is needed. It is best if you can run a trial with a bulk sample in an existing hopper with aeration devices, to make sure this approach will work. If you rely on fixing it on site, you have no idea how much air will be needed; this also gives you a problem because you need to have a suitable filtered vent on the hopper to deal with the air you are injecting, and it is hard to size this if you don't know the air flow needed.

- The effect of scale: It is tempting to think that if you are designing a large silo costing hundreds of thousands of dollars, the investment in the powder characterisation and the use of a rational hopper design method is justified, but if you are building a small bin or feeder hopper, costing only a few hundred dollars, it isn't worth doing, it looks like an "expensive luxury". But many years of experience at The Wolfson Centre has taught us that the opposite is true; although it is important to get the design of large silos right, especially for structural stability, the occurrence of flow problems is less frequent because often large outlets are needed for process purposes. But for small hoppers, the outlets are smaller so the likelihood of arching and rat-holing with a cohesive material is actually much greater, and although the hoppers cost little to build, the costs to the user of lost production due to poor flow can far outstrip the costs of the equipment. Hence, if handling a cohesive powder, it is actually even more important to invest in characterisation and hopper design for smaller vessels than for large silos.

CONCLUSION

The use of a rational method of hopper design for reliable flow, based on measured flow properties, is well established but is often not used due to a variety of factors, not least being the cost and the fact that many designs proceed to success without it.

The key to getting hopper designs that work successfully is to be mindful of the occasions when achieving success (reliable flow) really is helped by using the method. The "Rules of Thumb" presented above for deciding whether or not to use it, will give the user a guide to when he can get away without it, when it is essential, and when there is a risk to be judged.

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