13

Liquid–Solids Separation

In Chapter 12, we discussed the unit operations of evaporation and crystallization, both of which produce slurries or moist products (moist in this context could be water or some other solvent). It is now necessary to recover and dry the product for final storage and use.

Filtration and Filters

If an evaporation or crystallization process has produced wet slurry, we now need to filter it to produce a nearly dry cake, prior to drying. It is also possible that, in filtration, we are looking at a process to remove solid particles from a liquid product stream but the principles are the same.

Filtration is defined as the separation of solid particles from a liquid stream by forcing the slurry through a filter medium that allows the liquid to pass through, leaving the solids behind. This unit operation requires a pressure differential to force the fluid through the medium. The pressure differential can be either positive or negative, meaning that the upstream pressure can be above atmospheric pressure, or negative, meaning that a vacuum is pulled on the downstream side of the filter, "sucking" the fluid through the medium.

A simple diagram of a filter might look like that shown in Figure 13.1.

Materials that are too large to pass through the holes in the filter media are retained and build up into a filter cake and those smaller pass through into and with the filtrate.

Chemical Engineering for Non-Chemical Engineers, First Edition. Jack Hipple.

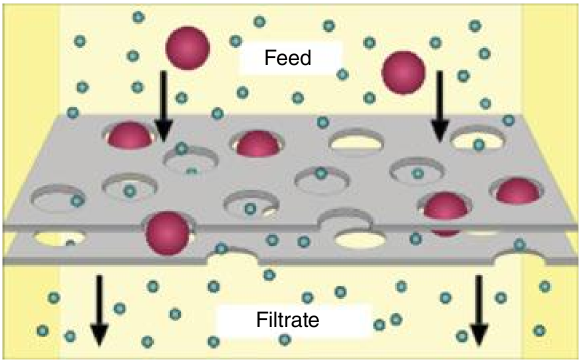


Figure 13.1 Basics of filtration. Source: Wikiwayman, https://commons.wikimedia.org/wiki/File:FilterDiagram.svg. Used under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/deed.en. © Wikipedia.

Filtration Rates

The rate at which liquid flows through the solids will depend on a number of factors:

1) Pressure differential across the medium (similar to the discussion in Chapter 7 on fluid flow)
2) The liquid properties such as density, viscosity, and surface tension
3) Particle size and particle size distribution of the solids being filtered (this would be similar to the difference we see in the rate of coffee production through coarse vs. espresso coffee grounds)

Many types of slurries have particle sizes small enough to clog the pores of a particular filter medium, thus "blinding" it off. In these cases a filter aid is preloaded on to the filter medium to provide a barrier between the fine particles and the filter cloth or medium. Inert materials frequently used for this purpose include sawdust, carbon, diatomaceous earth, or other large particle size materials.

Filtration can be a batch or continuous unit operation. If done continuously, there must be a mechanism to constantly remove some of the filtered material. If batch, the filtration is continued until the space between the filter leaves is full or the pressure differential possible with the process is reached. In any design, there must be a pressure differential to make the fluid pass through the solids. This pressure differential can be produced by pumps on the upstream side of the filter, vacuum on the downstream side, or some combination of both as a function of time.

Filtration Equipment

One of the most commonly used continuous filtration processes is what is known as *rotary vacuum* filtration, as illustrated in Figure 13.2.

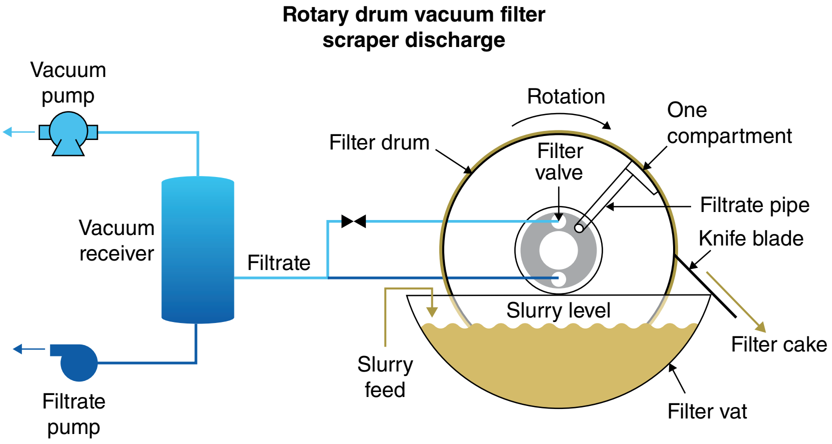


Figure 13.2 Rotary vacuum filter. Source: Reproduced with permission of Komline.

In this process, liquid is fed into a feed vat and "sucked" up on to the filter cloth, which rotates on a rotating drum. The vacuum is provided through a sealed system within the drum and connected to an external vacuum receiver and pump. As the cake travels around the drum (rotating clockwise), it is "dewatered" and then as it reaches the other side of the drum, the cake is scraped off as a filter cake and sent on for further processing (drying and storage), as shown in Figure 13.3.

In the mineral industry, filtration is used to recover mining cake and it is often sufficiently dry so as not to require a knife blade or other removal device—a simple sharp turn of the belt causes the cake to drop off the filter media. Another approach occasionally used for cake removal is a rotating brush system.

In addition to these types of continuous belt filters, there are other types of commercial filters. One is a semicontinuous filter known as a plate and frame filter. This used filter cloths wrapped around a frame with space between to serve as the reservoir to hold the solids. When the spaces are filled, the filter is shut down and the collected solids are removed, usually by a pressure source, into a collection pit, as shown in Figure 13.4.

If the fluid being filtered is the product of interest and the objective is to remove large-sized contaminants, gravity filtration, possibly supplemented by vibration, may also be used.

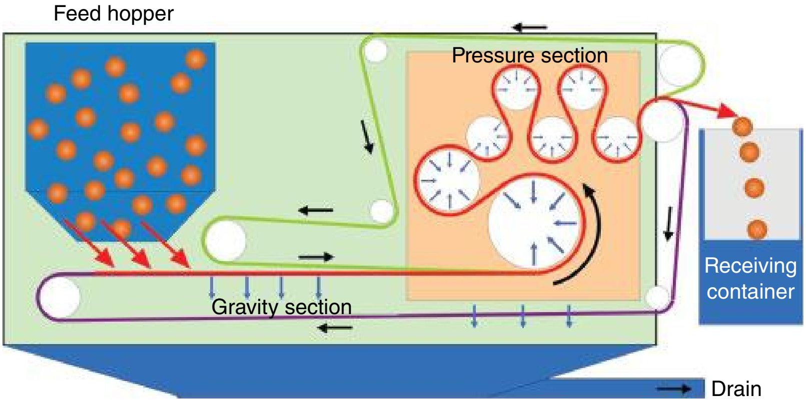


Figure 13.3 Belt filter. Source: Wikiwayman, https://commons.wikimedia.org/wiki/File:BeltPress.svg. Used under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/deed.en. © Wikipedia.

Figure 13.4 Plate and frame filter. Source: Wikipedia Public Domain License, http://fr.wikipedia.org/wiki/Utilisateur:Roumpf

Some of the design and operational parameters of filters and the symbols used in this area are the following:

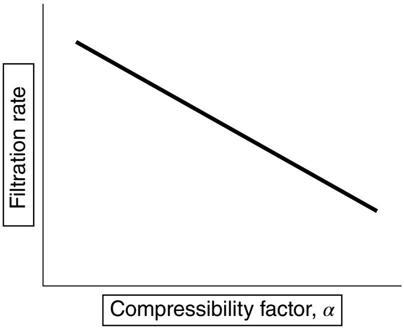
V refers to the volume of filtrate.

P or ΔP refers to the pressure or pressure differential across the filter and its medium.

ω (omega) is used to refer to the weight of solids per unit volume (#/ft^3, kg/m^3).

α (alpha) is used to describe the *compressibility* of the filtered cake. The higher the α, the more compressible is the cake, meaning that as the pressure is increased on the filter cake, the void volume decreases, slowing the filter rate. You can consider sand and rubber at opposite extremes of this value.

Figure 13.5 Filtration rate versus cake compressibility.



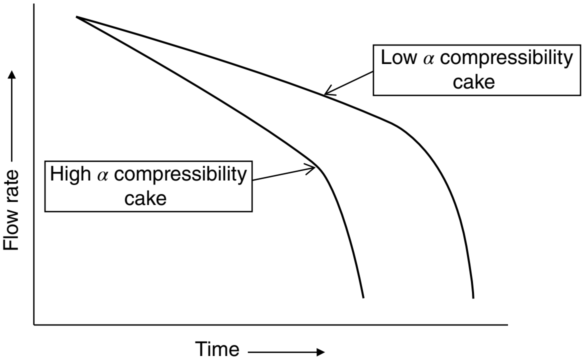


Figure 13.6 Flow rate at constant pressure with high and low compressibility cakes.

If we were to plot filter rate as a function of compressibility, we would see a graph as in Figure 13.5.

There are two basic ways of running a filtration operation—constant pressure or constant rate, though it is possible to combine one with the other depending upon practical limitations.

If we run the filtration at constant pressure, the filter cake will build up over time, providing additional resistance to the flow of fluid. The degree to which this happens will depend, in part, on the compressibility of the cake. A flow versus time diagram would look like as shown in Figure 13.6. In this figure is also displayed what the flow rate versus time curve would be seen with a more compressible (higher α) cake.

A more compressible cake, with a higher α, will tend to fill in the voids in the filtered solids more rapidly as the filtration progresses. At some point in time, the flow of filtrate becomes too low and uneconomical, and the filter is shut down, the cake removed, the filter medium washed, and the process restarted. The washing process and its fluid rates will be also affected by the physical properties of the solids recovered.

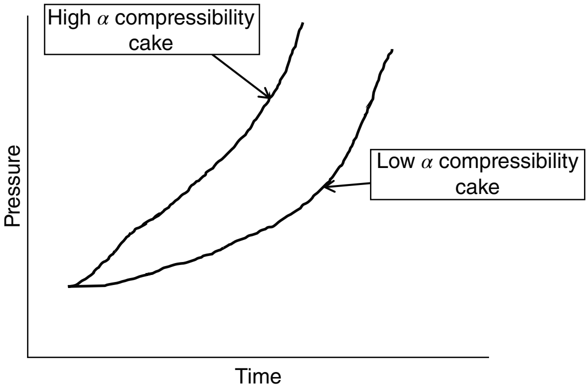


Figure 13.7 Pressure requirement versus time for constant rate filtration and high and low compressibility cakes.

If we desire to have constant flow, then the pressure must increase with time to overcome the pressure drop increase as the filter cake increases in thickness over time, as shown in Figure 13.7.

The general design equation for a filtration integrates the flow, pressure, solids content, and cake compressibility as follows:

$$V = \frac{PA^2\theta}{\alpha w}$$

where

V = volume of filtrate
P = system pressure
A = area of filter medium
θ = time
α = cake compressibility
w = solids concentration in mass/unit volume (i.e., #/ft^3)

If we increase the pressure, area, or length of time, we will get increased filtration rate. If we increase the cake compressibility or the solids content in the slurry being filtered, the filtration rate will drop.

In most cases, the solids recovered on a filter media will need to be washed to remove the last quantities of mother liquor from the original crystallization. In rare cases, where extreme purity is needed, the solids may be redissolved, recrystallized, and refiltered. As previously mentioned, the principles of design and performance would be the same.

Centrifuges

All of us have seen and used a centrifuge device in our daily lives—our home washing machines. Centrifuges are filters with the addition of centrifugal force to increase the pressure drop across the filter and increase the flow rate and/or amount of fluid passed through.

Figure 13.8 shows an illustration of a commercial continuous centrifugal separator being used to separate oversize particles from a slurry. The degree of separation can be controlled by design variables such as rotational speed and the choice of internal screens. It is also important to remember that any mechanical device of this kind will affect the particle size and particle size distribution of filtered solids due to the mechanical and abrasive forces acting on the solids while being separated.

The efficiency or added force of a rotational centrifuge is proportional to its radius and angular velocity squared, or $r\omega^2$. They can be batch (as in a home washing machine) or continuous; if a mechanism for continuous removal of the filtered cake is provided (in Figure 13.8), an internal screw conveying device is used to accomplish this. The spinning pushes the mother liquor through the filter medium, and in a semicontinuous fashion, a "pusher" moves through the middle of the machine, pushing the solids out to a temporary storage area for additional processing such as drying, particle size reduction, or agglomeration.

Operational and design issues for these types of devices include the following:

1) Specific gravity differences between the liquid and solids being filtered
2) Solids concentration in the feed
3) Liquid throughput rate
4) Rotational speed
5) Degradation of particle size due to the mechanical contact and pushing (not a concern with simple filters)

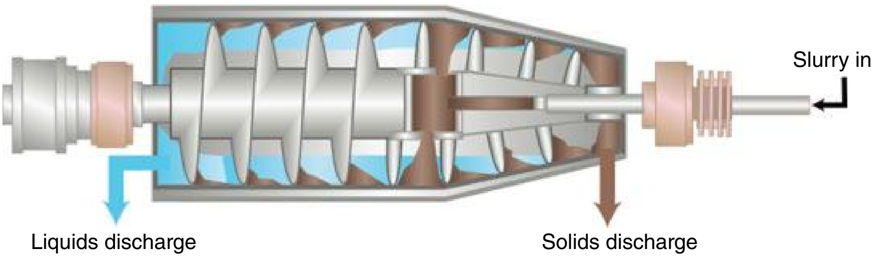


Figure 13.8 Decanting centrifuge. Source: Chemical Engineering Progress, July 2012, pp. 45–50. Reproduced with permission of American Institute of Chemical Engineers.

6) Particle shape and compressibility
7) Rinsing and washing capabilities
8) Density and viscosity properties of the liquid phase
9) Efficiency of solids capture
10) Liquid clarity leaving the centrifuge

A summary of the various types of centrifuges and their capabilities in different aspects is shown in Table 13.1.

Table 13.2 shows another view of the various performance aspects of different types of centrifuges.

This type of equipment will invariably involve tests with numerous vendors who specialize in each of these types of equipment.

Particle Size and Particle Size Distribution

Regardless of what kind of filter or centrifuge is used, the particle size and particle size distribution will affect its performance. Smaller particles will have a tendency to blind off the filter media, and the acceleration rate of smaller versus larger particles in a centrifuge will produce a nonuniform cake composition (in terms of particle size). This difference may need to be taken into account in downstream processing in drying and solids handling.

Liquid Properties

Again, regardless of the type of filter being used, the properties of the liquid, from which the solids are being filtered, will greatly affect the flow of liquid through the filter. The effects of liquid properties will be similar to those discussed earlier in the unit on fluid handling, especially if a centrifuge is used. A high viscosity liquid will flow through the solids and filter media slower; a high density fluid will flow through faster. If we have an unusual fluid that has response to shear, its viscosity will be affected by the rotational speed of the centrifuge.

Summary

Liquid–solids separation is an important unit operation in chemical engineering. The ability of a filter to separate a solid from a liquid depends on the physical properties of the liquid and solid being filtered, the pressure drop across the filter, the nature of the solids in terms of particle size, particle size distribution, and compressibility.

Table 13.1 Centrifuge choices.

	Vertical basket					
	Manual discharge	**Peeler discharge**	**cGMP**	**Horizontal peeler**	**Inverting filter with PAC**	**Decanter**
Diameter, mm	200–1600	800–1800	Up to 1250	250–2000	300–1300	~1500
Operation	Batch	Batch	Batch	Batch	Batch	Continuous
Cake washing	Yes	Yes	Yes	Yes	Yes	No
Discharge	Manual	Automatic	Automatic	Automatic	Automatic	Automatic
Containment	No	Yes	Yes	Yes	Yes	Yes
Solids filterability	Low to medium	Low to medium	—	Medium	Medium	—
Volume capacity	Low	Medium to high	—	High	Medium to high	High

Source: Chemical Engineering Progress, July 2012, pp. 45–50. Reproduced with permission of American Institute of Chemical Engineers.

Table 13.2 Comparison of various types of centrifuges.

Performance parameter	Vertical basket	Horizontal peeler	Inverting bag	Screen bowl	Scroll screen	Pusher	Vibratory	Imperforate basket	Tubular	Solid bowl	Disc
Particle size, μm	10–100	10–100	10–100	50–5000	100–50,000	15–100	500–10,000	1.0–1,000	0.01–100	5–5,000	0.1–100
Wt.% solids in feed	5–50	5–50	5–50	5–40	30–80	30–60	40–80	1–50	<0.1	0.5–60	0.1–5
Liquid flow rate, gal/min	1–150 (feed)	1–150 (feed)	1–50 (feed)	1–500	5–200	5–250	300–1,000	1–100	<25	1–600	2–600
Solids production rate, ton/year	0.01–1.5	0.01–1.5	0.01–0.5	1–100	40–350	5–50	5–50	0.01–3	<0.003	0.05–100	0.001–1.5
Centrifugal force, m/s^2	500–1500	500–1500	500–1500	500–2000	500	500	500–2,000	1,000–20,000	4,000–10,000	1,000–10,000	5,000–10,000
Solids wash	E	E	E	F	F–G	F–G	P	NA	NA	P	NA
Solids capture	E	E	E	G	G	G	G	E	E	E	E
Liquid clarity	G–E	G–E	G–E	F–G	F–G	F–G	F	E	E	E	E

Source: Chemical Engineering Progress, August 2004, pp. 34–39. Reproduced with permission of American Institute of Chemical Engineers.
E, excellent; G, good; NA, not applicable; P, poor.

Back to Coffee Brewing

The ground coffee that is used in a coffee brewing machine will have different particle size and different particle size distribution depending on the grinding setting at the store or in last minute grinding at home. These grounds, of whatever average size and size distribution, are placed in a filter. These filters are of various shapes and geometries. The flow rate through the coffee filter along with the grind nature will affect the "strength" of the coffee in terms of its taste. Percolator coffee brewers, which use a recycling of filtrate through the ground beans, will use very coarse grinds, while espresso coffee machines will use extremely fine particles to produce a very strong coffee flavor with a once through brewing. The temperature of the water used will affect not only the temperature of the final cup of coffee but also its viscosity and how fast it flows though the grounds. The final step in making coffee is a chemical engineering filtration process.

Discussion Questions

1. If you are running filters or centrifuges, is the basic information about flow rates versus pressure known?
2. If a filter with a pre-coat is used, are the limitations of its particle size limitations known?
3. Depending on whether constant pressure or rate filtration is being used, how was that decision reached? Should it be revisited?
4. Should the choice of continuous versus batch be revisited?
5. If a centrifuge is being used, what was the basis for its design, type, and vendor made? How reliable is its operation?
6. Would a different particle size distribution feeding either a filter or centrifuge improve their operation? If so, how could this be achieved?

Review Questions (Answers in Appendix with Explanations)

1. The driving force for filtration is:
   A __Pressure differential
   B __Concentration differential

C __Temperature differential
D __Temperament differential

2 A pre-coat on a filter medium may be required if:
A __It is cold in the filter operations room
B __The operating instructions say so
C __The particle size of the solids is greater than the hole size in the filter medium
D __The particle size of the solids is smaller than the hole size in the filter medium

3 If the filtration is run under constant pressure, the flow rate will ____ with time:
A __Drop
B __Stay the same
C __Increase
D __Need more information to know

4 If the filtration is run to produce constant volume output, the pressure will ____ with time:
A __Drop
B __Stay the same
C __Increase
D __Rise by the cube of the change in flow

5 Raising the solids concentration in a filter feed, with other variables unchanged, will _____ the filtration rate:
A __Increase
B __Decrease
C __Not affect
D __Drop by the square root of the solids concentration change

6 Increased compressibility of a filtration cake will _____ the filtration rate over time:
A __Increase
B __Decrease
C __Stay the same
D __Increase by the square of the compressibility

7 A centrifuge adds what force to enhance filtration rate:
A __Gravity
B __Pressure
C __Centrifugal/centripetal
D __Desire for a faster rate

8 The rate of filtration in a centrifuge is proportional to the ____of the rotational speed:

A __Linearity
B __Square root
C __Cube
D __Square

Additional Resources

Norton, V. and Wilkie, W. (2004) "Clarifying Centrifuge Operation and Selection" *Chemical Engineering Progress*, August, pp. 34–39.

Patnaik, T. (2012) "Solid-Liquid Separation: A Guide to Centrifuge Selection" *Chemical Engineering Progress*, 108, pp. 45–50.

14

Drying

On the assumption that the material that has been filtered is the product of interest or if the “wet” product has come from some other part of a process or unit operation, it usually needs to be dried, meaning that the residual solvent or water needs to be evaporated to some degree. To what degree is primarily a function of customer requirements, but to some extent also the nature of the physical handling of the product after drying. An example of this latter case might be caking of the product while being stored or in shipping containers.

In order for a solvent or water to evaporate, energy must be supplied from some source and a driving force must exist. It normally comes from indirect heating with steam but could come from hot oil. A vacuum can be added to the process to increase the vapor pressure difference and accelerate the drying process. The drying can also be accomplished by direct contact with a hot air or gas stream, which then may need to be treated in some way to remove any entrained solid particles.

Since drying may involve a temperature increase in the solid material, we must also check for any possibility of product decomposition (from a quality standpoint) or possibly decomposition that may lead to a safety or reactive chemical incident.

We can view the general nature of a drying process in Figure 14.1. This graph shows what we would find if we ran a drying test on the wet solid.

At the start of a drying process, there is usually substantial moisture (or solvent content) on the surface of the solid. In this early stage, there is little mass transfer resistance of the moisture evaporating. It is based almost solely on the contacting between the solid and the drying gas.

As the drying process progresses, the moisture (or solvent) needs to diffuse to the surface of the solid to be able to contact the drying gas. This point, where the rate of drying begins to decline significantly, is referred to as the “critical moisture content” or CMC. The drying rate continues to

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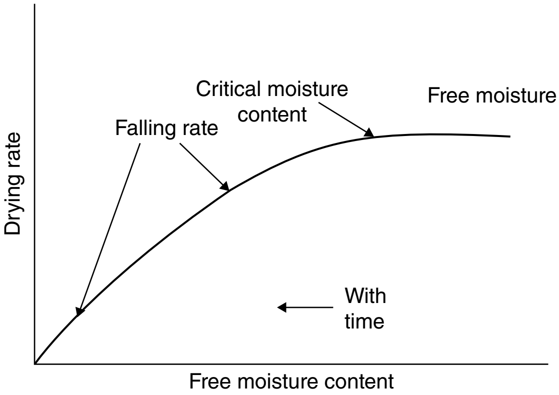

Figure 14.1 Drying rate versus residual moisture content.

fall as the residual moisture/solvent begins to need to overcome strong capillary surface forces within the pores of the solid. During these latter phases, the time it takes to remove the water/solvent increases significantly, and the economic value of achieving these low values must be weighed against the cost of the extended drying time and additional energy cost.

In general, the rate of drying will be proportional to the temperature differential between the drying heat source and the temperature of the material being dried as well as the area of the material being exposed to the drying medium and inversely proportional to the heat of vaporization. The contact area can be increased by agitation, tumbling within batch dryers, and baffling inside rotating equipment.

There are a number of commercial type dryers, including:

Rotary Dryers

These dryers can be either continuous or batch and can be direct heat fired or the water/solvent evaporated with the assistance of vacuum. Batch processing would be typically used in specialty and pharmaceutical applications where lot control is important.

A continuous countercurrent dryer would tumble the solids within an inclined rotary cylinder with a hot gas flowing countercurrently, with possible internal baffles to minimize sticking to the walls and maximize gas–solid contacting (Figure 14.2).

Figure 14.2 Rotary dryers. Source: Brookoffice, https://commons.wikimedia.org/wiki/File:Single_Shell_Rotary_Drum_Dryer.jpg. Used under CC BY-SA 3.0, http://creativecommons.org/licenses/by-sa/3.0. © Wikipedia.

Spray Dryers

In this dryer configuration a concentrated slurry or solution is passed through a spray nozzle, with high pressure drop. This atomizes the solution, creating a very large surface area and rapid drying rates. The drying medium is typically hot air or, in the case of some oxygen-sensitive products, a hot inert gas such as nitrogen (Figure 14.3).

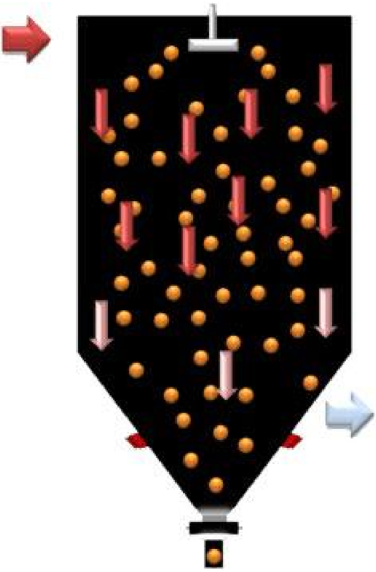

Figure 14.3 Schematic of spray drying. Source: https://commons.wikimedia.org/wiki/File:Spray_Dryer.gif. Used under CC BY-SA 3.0, http://creativecommons.org/licenses/by-sa/3.0. © Wikipedia.

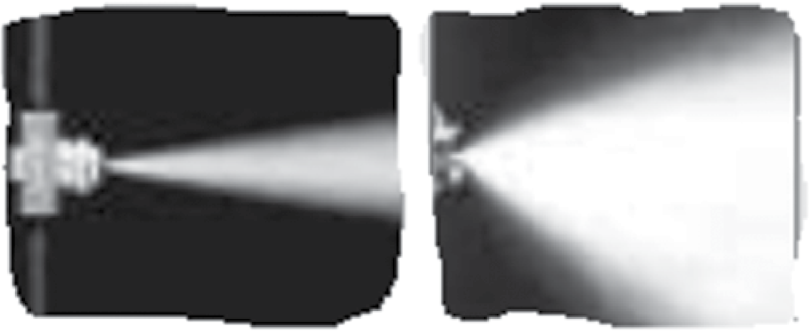

Figure 14.4 Spray nozzle for dryer. Source: Chemical Engineering Progress, 12/05. Reproduced with permission of American Institute of Chemical Engineers.

Since this dryer is contacting slurry with a fast velocity gas, which may cause some particle degradation, it is normal to see a cyclone and possibly a bag filter used to ensure that small particle solids are not discharged to the atmosphere.

The dryer requires a rather sophisticated spray nozzle to cause atomization of the slurry. Figure 14.4 shows an illustration of different discharge patterns from such a nozzle that will affect the drop size and drop size distribution. The patterns and liquid particle size distribution will also be affected by the liquid properties as well as the use of air to increase the degree of atomization.

If we recall some of the variables we discussed in the fluid handling unit, you can understand that pressure drop across the nozzle, density, viscosity, and spray stream particle size will have a great effect on the performance of such dryers.

Fluid Bed Dryers

The term "fluid bed" refers to a situation where the velocity of a gas stream is sufficient to suspend a solid. If this is done correctly, a great deal of turbulence and contact between the gas and slurry is generated, producing very rapid drying rates. The solid, if viewed from above, appears to be a suspended liquid. Any solid particle has a velocity at which it will be suspended by a gas flow. This will be a function of particle size and density, as well as gas properties. This is illustrated in Figure 14.5.

If the gas velocity is sufficient to suspend the wet solids, the drying rates will be very fast and the residence time will be low. This may be beneficial if short residence time is necessary due to temperature sensitivity. The downside of these dryers is that the turbulence will typically cause degradation in particle size and the need to use cyclones and scrubbers on the outlet gas stream to prevent significant discharge to the atmosphere.

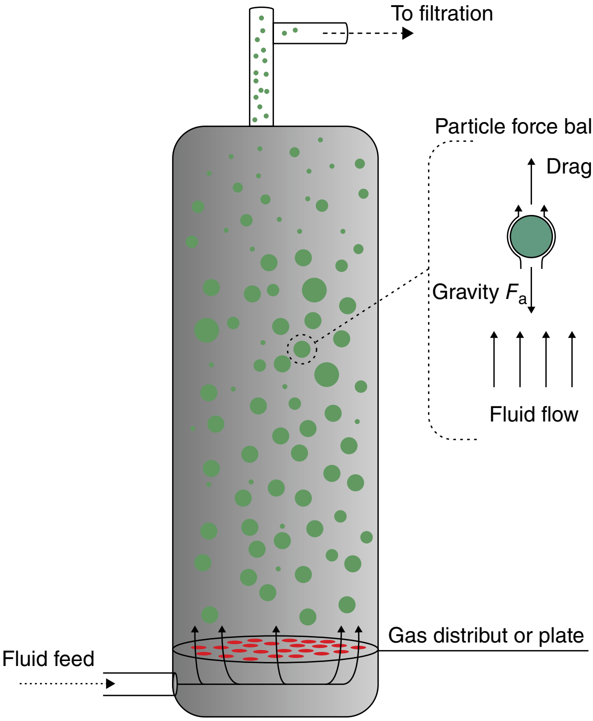

Figure 14.5 Fluidized bed particle forces. Source: https://commons.wikimedia.org/w/index.php?curid=3982684. Used under CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0/. © Wikipedia.

The wet slurry and hot gas enter through support plates with a velocity sufficient to suspend the solids. These types of dryers can also be designed so that the solids move from left to right across a decreasing flow and temperature of gas and finally discharging. The gas velocity must be balanced against the force required to lift the solids out of the dryer completely. Support and distribution plates, similar in concept to those used in packed distillation towers, are used to distribute the drying gas evenly as well as to prevent solids from leaving the bottom of the column.

Belt Dryer

This is a dryer where the wet solid is deposited on a moving belt and a slow velocity hot gas is moved countercurrently, with possible staged temperature control, as shown in Figure 14.6 (drying pasta).

Figure 14.6 Food belt dryer. Source: https://commons.wikimedia.org/wiki/File:DEMACO_DTC-1000_Treatment_Center_for_Fresh_Pasta_Production_(April_1995)_003_crop.jpg. Used under CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0/deed.en. © Wikipedia.

Freeze Dyers

When we need to dry very heat-sensitive materials (e.g., fruits and vegetables), it is not possible to expose them to any significant amount of heat. Most of the time, water is the material that needs to be removed and water (and other materials) has an interesting phenomenon known as a "triple point" in its solid–liquid–gas phase diagram as illustrated in Figure 14.7.

In the case of water, this "triple point" occurs around 0°C and 4 mmHg absolute pressure. Though it is expensive to produce vacuum, this is not so low as not to be economical for valuable food products such as coffee ("freeze dried"), nuts, fruits, and vegetables. It is a batch process where a high volume of product is put into a vacuum chamber and then left for a predetermined amount of time, the vacuum released, and the product then packaged. The type of equipment used in this drying process is usually a simple tray dryer with plates or shelves inserted into a chamber, the chamber sealed, vacuum created and held for a specific time, and then the vacuum released and product removed and packaged.

Summary

Drying is a unit operation used to remove water or solvents from products prior to final handling and storage. A drying curve is generated for any given product to develop a rough estimate of the cost and time involved in achieving

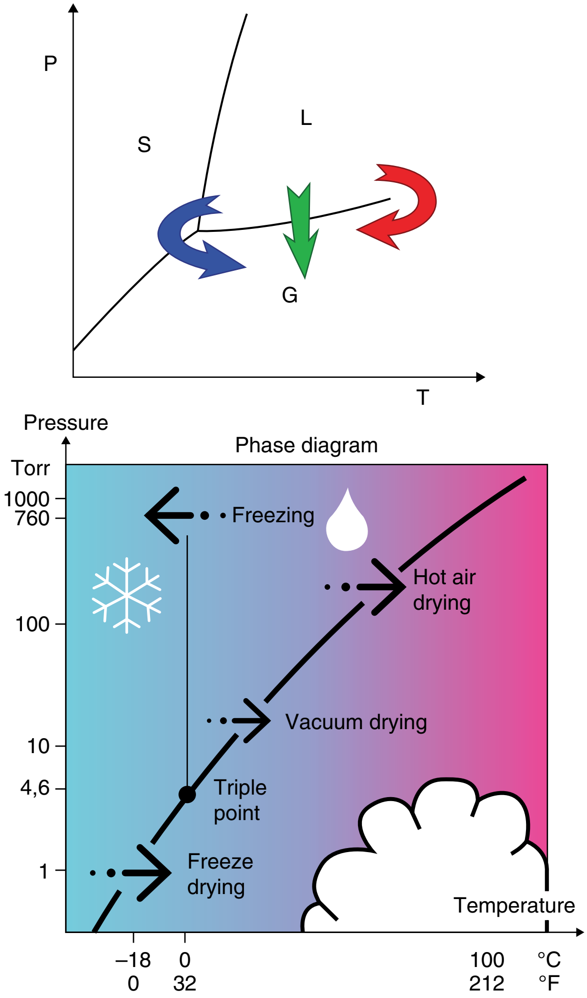

Figure 14.7 Phase diagrams with triple points. S, solid; L, liquid; and G, gas. Source: Used under https://commons.wikimedia.org/wiki/File:Drying.svg. © Wikipedia.

a given residual level. There are many different types of commercial equipment used, both batch and continuous. Vendors are normally heavily involved in specifying equipment through trials with customers, as much of the design data is empirically based. The degree of "dryness" or residual water or solvent will have a significant impact on further downstream processing such as solids handling.

Coffee Brewing and Drying

We normally don't think about drying associated with coffee brewing. We don't normally specify the moisture content of the coffee (in whatever form) being used. If it were an important variable, the way the coffee or its grounds are stored will affect the amount of water lost in storage. To a very minor degree, the degree of residual water content will have a minor impact on the concentration of the brewed coffee. One of the first commercial uses of freeze drying was in the manufacture of freeze-dried coffee. This drying and evaporation process, at low temperature and high vacuum, allows moisture to be removed without subjecting the coffee to high temperatures, thus minimizing the taste degradation of the coffee. Since this drying process is far more energy intensive than normal drying and evaporation, the cost of such coffee is generally higher.

Discussion Questions

1. Are the drying rate curves known for all the products being dried? What could affect these? What process conditions could affect?

2. Is your drying process robust enough to deal with variations in both customer requirements and changes in utilities?

3. How were the current drying processes chosen? Have alternatives constantly been reviewed?

4. How does your drying process affect particle size and particle size distribution? How does this affect your internal solids handling and your customer's use of your product?

5. If your dryer was capable of producing an extremely dry product, would that provide additional market opportunities?

Review Questions (Answers in Appendix with Explanations)

1. Drying is defined as the removal of ___ from a solid material:
   A __Solvent
   B __Coolant
   C __Water
   D __Spirits

2 Drying rate is affected by all but:
  A __Solvent concentration at any point in time
  B __Cost of vacuum or steam
  C __Agitation within the dryer
  D __Temperature difference between solid and heating medium

3 Key variables in the design and operation of a spray dryer include:
  A __Liquid or slurry to gas ratio
  B __Viscosity of fluid and pressure drop across the spray nozzle
  C __Temperature difference between hot drying gas and liquid
  D __All of the above

4 Design issues with rotary dryers include:
  A __Possible need for dust recovery
  B __Particle size degradation
  C __Dust fires and explosions
  D __All of the above

5 Freeze drying is a potential practical drying process if:
  A __A freezer is available
  B __The S–L–V phase diagram allows direct sublimation at a reasonable vacuum
  C __It is desired to have a cold product
  D __The plant manager owns stock in a freeze dryer manufacturing company

6 A drying rate curve tells us:
  A __How fast a solid will dry
  B __How much it will cost to dry a solid to a particular residual water or solvent level
  C __The drying rate curve as a function of residual water or solvent
  D __How the cost of drying is affected by the rate of inflation

7 Auxiliary equipment frequently needed for a drying process include:
  A __Cyclones and scrubbers
  B __Backup feed supply
  C __Customer to purchase product
  D __Method of measuring the supply chain

Additional Resources

Heywood, N. and Alderman, N. (2003) “Developments in Slurry Pipeline Technology” *Chemical Engineering Progress*, 4, pp. 36–43.

Langrish, T. (2009) "Applying Mass and Energy Balances to Spray Drying" *Chemical Engineering Progress,* 12, pp. 30–34.

Moyers, C. (2002) "Evaluating Dryers for New Services" *Chemical Engineering Progress,* 12, pp. 51–56.

Purutyan, H.; Carson, J., and Troxel, T. (2004) "Improving Solids Handling During Drying" *Chemical Engineering Progress,* 11, pp. 26–30.

15

Solids Handling

Safety and General Operational Concerns

As was the case with filtration and drying, this area of chemical engineering is rarely taught as part of chemical engineering curricula, and as a result, most of the science and design in solids handling is in the knowledge base and experience of vendors and engineering specialists within large corporations who handle solids as a significant part of their business. Since there is little basic training in this area, there are some sad side effects that are seen in industry:

1) Start-up times in plants handling solids are significantly greater than those handling just liquids and gases.
2) After start-up is over, the final operational conditions may vary significantly from the intended design.
3) Serious and catastrophic dust explosions and fires result from the lack of knowledge of the flammability and explosion hazards of solids and dusts. These fires and explosions occur most frequently where solids are concentrated or energy input is significant, such as in hoppers and silos, grinders and pulverizers, conveying systems, and mixing/blending equipment.

We tend to see most dust explosions in the food, wood, chemical, metal, rubber, and plastics industries where the basic materials have some natural flammability.

One of the important differences between solids and their bulk liquid and gas counterparts is the fact that solids can have different particle sizes (liquids can be in this area as well if there is an atomization or spraying process involved) when they have significant differences in surface area and energy. Here are some examples of materials and natural surface area differences:

Chemical Engineering for Non-Chemical Engineers, First Edition. Jack Hipple.

Table 15.1 Particle size illustrations.

Beach sand	100–10 000 μm
Fertilizer, limestone	10–1000
Fly ash	1–1000
Human hair	40–300
Cement dust	4–300
Coal dust, milled flour	1–100
Smoke from synthetics	1–50
Iron dust	4–20
Smoke	0.01–0.1
Paint pigments	0.1–5
Smoke, natural materials	0.01–0.1

Table 15.2 Strength of flame front for solids.

St 0:		*0*	Silica
St 1:	0–200 bar-m/s	Weak	Milk, zinc, sulfur, sugar, chocolate
St 2:	200–300	*Strong*	Cellulose, wood, polymethylmethacrylate
St 3:	>300	*Very strong*	Al, Mg, anthraquinone

Solids have been classified into general hazard classifications, similar to what is done with liquids and their flash points:

Even a material as mundane as sugar has significant fire and explosion potential, as seen in the Chemical Safety Board video in 2006, reviewing the dust explosion disaster at Imperial Sugar. A fine sugar dust explosion can generate a pressure in excess of 100 psi in less than 100 ms and can generate a flame velocity of over 500 ft/s. The lower limit for flammability of sugar (analogous to the lower explosive limit (LEL) of a flammable liquid) is approximately 9%, far lesser than the normal oxygen content of air.

The assessment of potential fire and explosion hazards with solids and dusts is a bit more complicated than the fire triangle discussed in Chapter 2. We normally represent it in the diagram shown in Figure 15.1.

We need not only the fuel (the solid), oxygen, and a source of ignition but also a way of either suspending the solid dust (increasing its surface area) or concentrating it by confinement.

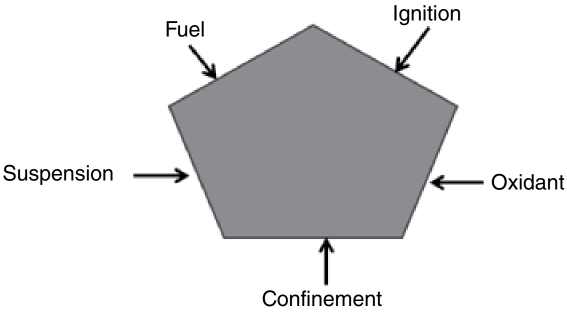

Figure 15.1 Requirements for a dust explosion.

Prevention of dust explosions concentrates in these following areas:

1) Understanding the flammability of limits of the solids being handled and how they are affected by particle size and particle size distribution
2) Minimizing points where solids can concentrate and build up, such as joints
3) Proper use of explosion relief devices and proper vent sizing
4) Pressure sensors within solids transport systems
5) Necessary grounding
6) Inerting with noncombustible gases when necessary and checking for integrity of vacuum seals
7) Use of nonconductive coatings

There are a number of tests that are used to evaluate the various aspects of solids safety:

Explosion severity test measures the maximum pressure generated by a solids explosion. This is somewhat analogous to the maximum explosive pressure discussed earlier for liquids.

Minimum ignition energy (MIE) is identical to the same type of value for liquids and gases. There will always be some amount of energy necessary to initiate a fire or explosion.

Minimum autoignition temperature (MAIT) of dust cloud is again analogous to the same value for a liquid or gas.

Minimum explosive concentration (MEC) of dust in air is analogous to the LEL for a liquid or gas in air. Below some level of fuel (solid), there is insufficient fuel to sustain the fire.

Limiting oxygen concentration (LOC) is again identical to the same measurement obtained for liquids. There is a minimum oxygen content in the gas phase, which is required for a solids fire to sustain itself.

Electrostatic chargeability test (ECT) provides a measure of the ability of a solid to hold a charge, which then may serve as an ignition source later on.

Solids Transport

Solids need to be moved for various reasons:

1) Unloading of solid raw materials to be used in reactions
2) Transfer of solids from a dryer into a solids classification, size reduction unit operation, or directly into storage
3) Loading of outgoing trucks or barges

Solids transport is done in many different ways:

1) Screw conveyors
2) Bucket elevators
3) Belt conveyors
4) Pneumatic conveyors

Screw conveyors are tubular devices with an internal rotating helical screw (referred to as a "flighting") that moves the solid from one place to another. A general diagram of screw conveyor is shown in Figure 15.2.

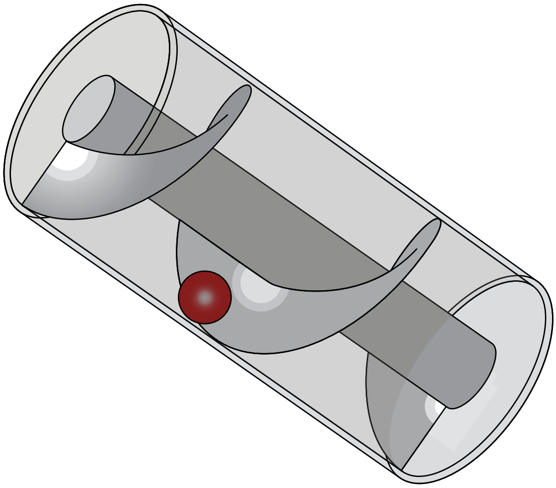

Figure 15.2 Screw conveyor. Source: Silberwolf, https://commons.wikimedia.org/wiki/File:Archimedes-screw_one-screw-threads_with-ball_3D-view_animated_small.gif. Used under CC BY-SA 2.5 https://creativecommons.org/licenses/by-sa/2.5/deed.en. © Wikipedia.

The primary design variables are the diameter and depth of the trough, the size and rotational speed of the screw, the angle or pitch of the screw, the depth of solid during transport, and the clearance between the screw and the wall. If the solid has significant dust explosion potential, there also may be safety relief, inerting, and monitoring systems.

Another view of an operating screw conveyor is shown in Figure 15.3.

Figure 15.3 Operating screw conveyor. Source: https://commons.wikimedia.org/w/index.php?curid=9515471. Used under CC BY 3.0 https://creativecommons.org/licenses/by/3.0/deed.en. © Wikipedia.

Design variables would include the following:

1) Speed of the transfer screw.
2) Wall clearance between the screw and the wall. Close clearance will ensure not only more uniform directional flow but will also cause wear and potential corrosion products entering the product being transferred.
3) "Starved" or full-fed transport. This will affect the rate of transport, the degree of abrasion, and the degree of particle size attrition.
4) Need for cooling or heating on the jacket of the screw conveyor.
5) Screw conveyors, due to the abrasive nature of the transport mechanism, can also provide some mixing within them as well as reduction in particle size while being conveyed.

When a screw conveyor is being used to control and feed material into a reaction or mixing system in a controllable fashion, it is often referred to a screw meter.

The energy consumption of a screw conveyor will depend on a number of system properties, including auger and screw diameter as shown in Figure 15.4.

Costs will also be affected by the solids density (the higher, the more energy needed), the RPM of the screw (the faster, the more energy consumed, and the greater the particle size attrition), and the inclination angle.

Bucket elevators are used to transport solids vertically as shown in Figure 15.5.

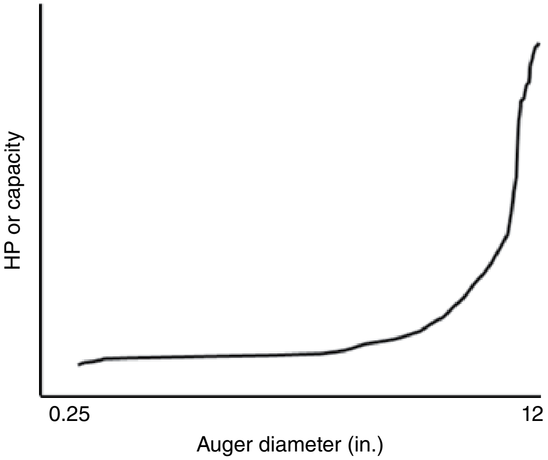

Figure 15.4 Screw conveyor energy costs.

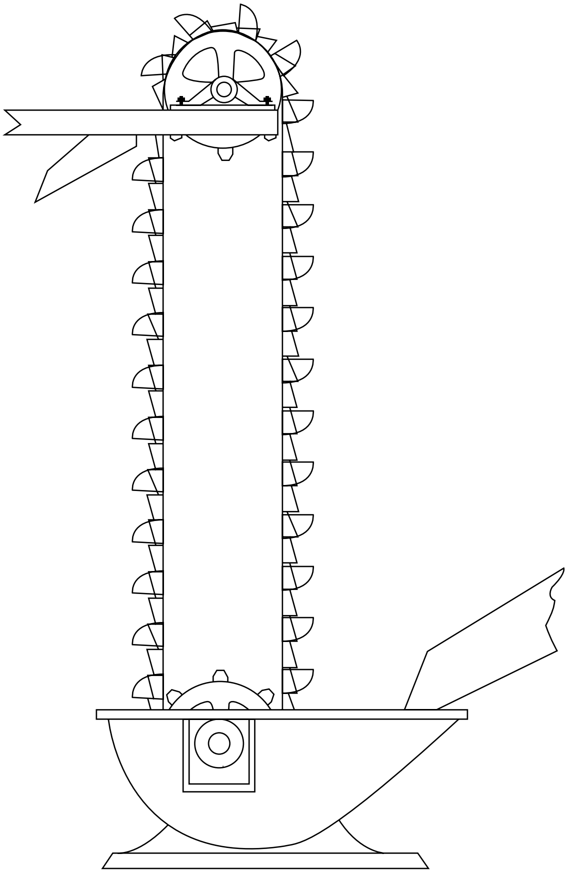

Figure 15.5 Bucket elevator. Source: Henry Kreitzer Benson, https://commons.wikimedia.org/wiki/File:Bucket_elevator_drawing.JPG. © Wikipedia.

Figure 15.6 Mineral belt conveyor.

Belt conveyors, frequently used in large-volume transport in the mining and mineral industry, are illustrated in Figure 15.7.

This conveyor shown in Figure 15.6 is carrying coal, while an illustration of the one carrying sulfur from a mining operation on to a ship is shown in Figure 15.7.

Design variables will include speed, width, and energy consumption. The general design equation for a belt conveyor would be expressed as $Q = \rho AV$, where Q is the amount of material transported, ρ is the density of the material, A is the cross-sectional area of the solid on the belt, and V is the velocity of the belt.

Pneumatic Conveyors

Given a sufficient amount of gas, a solid particle can be "lifted" and transported along with the gas. This is called pneumatic conveying. Figure 15.8 shows a generic flow diagram of such a system, along with its auxiliary support equipment.

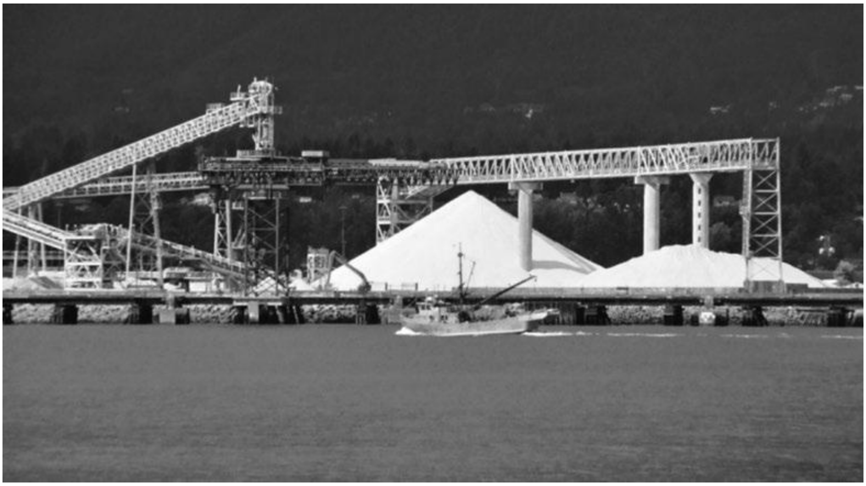

Figure 15.7 Belt conveyor for sulfur. Source: Leonard G, https://commons.wikimedia.org/wiki/File:AlbertaSulfurAtVancouverBC.jpg. Used under CC SA 1.0 https://creativecommons.org/licenses/sa/1.0/. © Wikipedia.

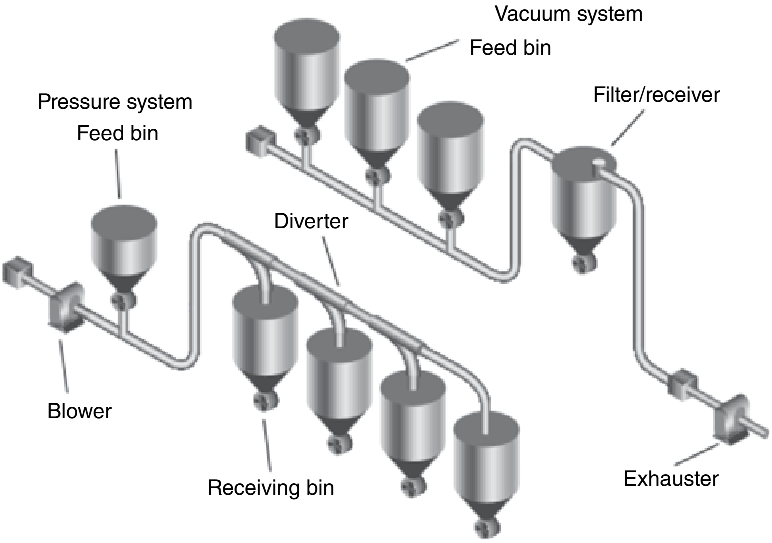

Figure 15.8 Pneumatic conveying systems. Source: Chemical Engineering Progress, 12/05, pp. 22–30. Reproduced with permission of American Institute of Chemical Engineers.

Material is typically fed into a storage bin via one of the many solids transport devices discussed earlier. In this case, a screw conveyor is being used. Material from a bin is combined with an airstream (this stream could be an inert gas such as nitrogen if there was a flammability concern) that combines with the solid and is conveyed, with sufficient gas velocity, into a receiving bin. This bin could be used for final storage or for unloading into hopper car. As we can see, there are numerous controls on this system to measure level, gas flow, and so on.

Some of the general design considerations and concerns are as follows:

1) Vacuum or Pressure Driven. The gas stream needs a pressure differential to flow. This can take the form of a positive pressure on the upstream side or vacuum/suction on the receiving side. There are pros and cons to both. A pressure-driven system may cause leaks of solids and dust to the atmosphere. A vacuum system may allow air leakage in, which may cause oxidation of the solid or create a hazardous atmosphere. In general, for the same pressure drop, the vacuum is more expensive than the pressure-driven system.
2) Particle Size Distribution. If the solids being transported have a wide range of particle size, the smaller particles will tend to travel faster, and the solids distribution in the receiving vessel will be different than that of the original storage vessel. This will need to be taken into account when designing the receiving vessel to make sure adequate flow of solids out of the bottom of the receiving vessel is unhindered.
3) Abrasion. If solids are transported at a high rate in a gas stream, we may need to worry about abrasion to the transporting pipes. This will depend upon the natural abrasiveness of the solids, the velocity of the gas stream, and the material used for the transport pipe.
4) Friability. Different solids have different degrees of what is known as "friability," that is, their susceptibility to breaking up into smaller particles when subjected to impact and shear force. A high gas velocity and many bends in the transport system will tend to increase the likelihood that there will be a different particle size distribution as well as smaller particles in the receiving vessel.
5) Moisture Content. Moisture and humidity can affect solid particles' adhesion to each other. The humidity of the conveying airstream may need to be controlled and monitored. If a vacuum system is used, leakage of ambient air into the system may also bring moisture into the system.

This transport can be done in two different fashions, *dilute phase* and *dense phase*. Dilute phase refers to a condition where the solid being transported is suspended in the air. This may be preferable for lower-density solids being transported over long distances. When the gas velocity is high and the particle size small, a dust collection system is usually employed to prevent discharge into the atmosphere.

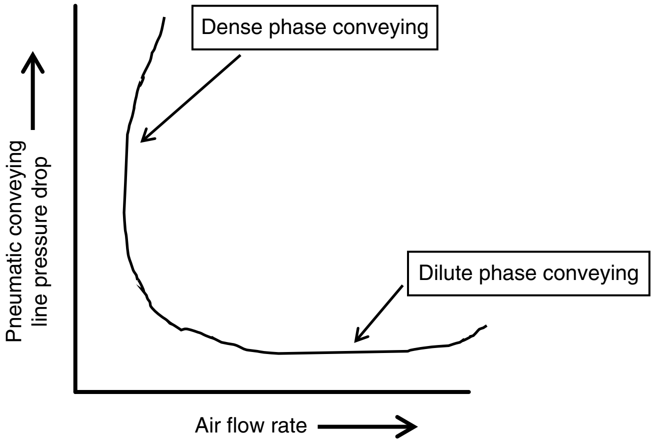

Figure 15.9 Pressure- versus vacuum-driven conveying systems.

A dense-phase system uses a small amount of gas and "pulses" the solids through the pipeline, with the pipeline nearly full of solids. This is more appropriate for denser solids and where concerns about friability and fines generation are present. There may still be a need for dust collection, but not nearly as large or sophisticated. There will also be less particle degradation, but more pressure drop.

Figure 15.9 shows the general relationship and extremes of the two types of design.

We can see the trade-off between airflow rate and pressure drop. Another important point is to not design or attempt to operate a pneumatic conveying system between these two extremes. This will cause pulsation and surging of flow, as the solids will sometimes be in the gas phase, and at other times will not.

Just as complicated piping networks need proper labeling and safety protocols to prevent liquids and gases from going into the wrong vessels, the same is true about pneumatic conveying systems. It is important to properly designate the routing of solids transport and provide safety interlocks so that the wrong product does not wind up in the wrong storage system or hopper car.

The energy used in a pneumatic conveying system will depend upon the amount of material being transported as well as upon whether the material is being elevated (such as into a storage silo from ground level).

Figures 15.10 and 15.11 show the energy used in such a system as a function of amount of material, length, and elevation.

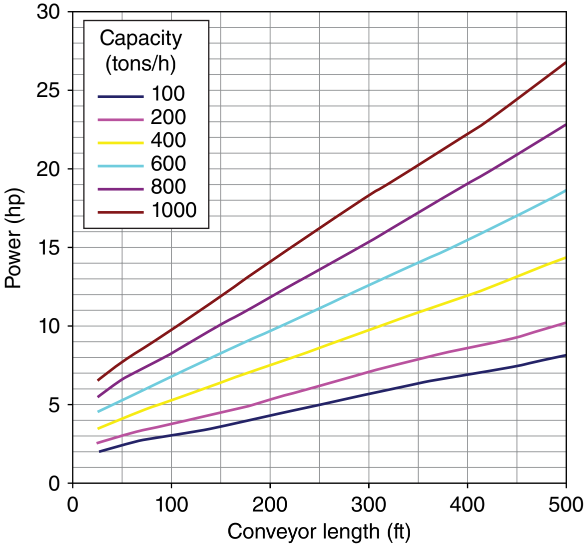

Figure 15.10 Pneumatic conveyor energy use versus length used. Source: Reproduced with permission of Engineering Toolbox.

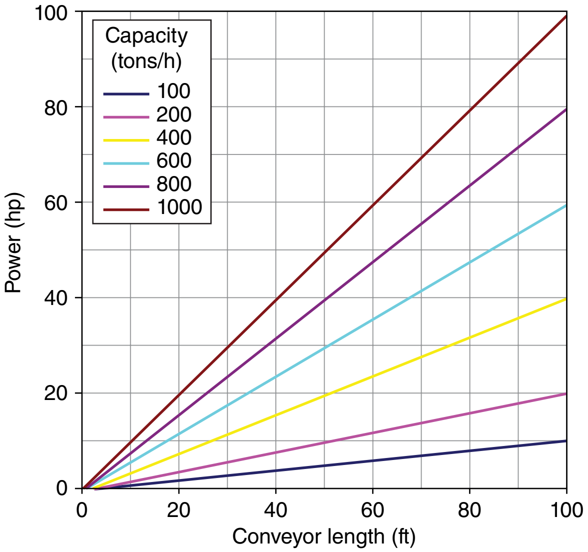

Figure 15.11 Pneumatic conveyor energy use versus lift used. Source: Reproduced with permission of Engineering Toolbox.

Solids Size Reduction Equipment

Frequently, especially in the mining of minerals and ores, the size of the solids is much greater than that desired in a downstream use. This requires that the raw solids be reduced in particle size, primarily through the use of mechanical energy.

There are many types of particle size reduction equipment, including hammer mills, rod mills, pulverizers, cage mills, roll crushers, attrition mills, and others. They each have their area of unique use and application with a great deal of overlap, normally requiring multiple vendor trials and evaluations. One common factor is the noise associated with these types of equipment, and it is normal to have advanced hearing protection and/or equipment isolation. An additional common factor is a relatively large energy use that increases as the desired particle size decreases.

We will review some of these in more detail. A hammer mill is basically a rotating shaft with hammer arms attached, but free to rotate. Solids size reduction is a function of starting particle size, hardness difference between the solid and the rotating arm, and the amount of time. A wood chipper would be a good analogy. A typical hammer, with its internals, is shown in Figure 15.12.

Another type of mill used to crush rocks and ores is a rod mill, shown in Figure 15.13.

Industrially, inside these mills are thousands of rods that are free to rotate and provide the impact force.

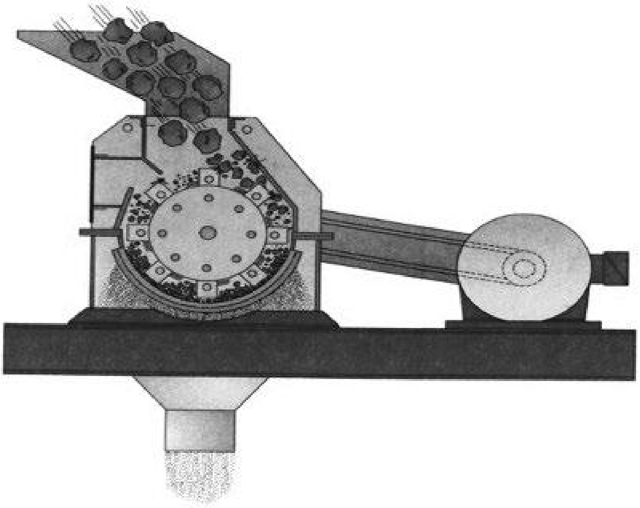

Figure 15.12 Hammer mill. Source: Courtesy of Schutte-Buffalo Hammermill.

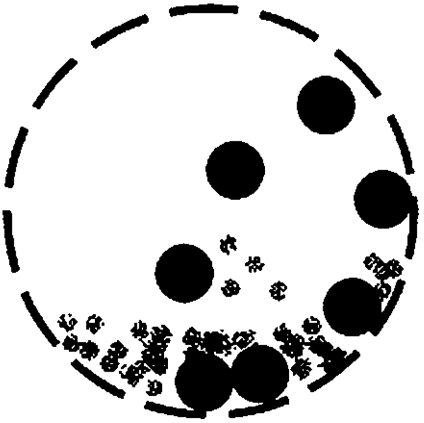

Figure 15.13 Rod mill. Source: https://commons.wikimedia.org/wiki/File:Ball_mill.gif.

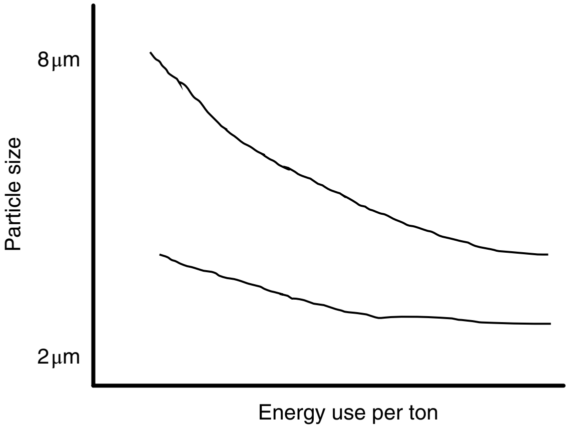

Figure 15.14 Relative energy input versus particle size required.

Attrition mills are similar in the fact that they use grinding media, but the media are typically spherical in shape and are used for pigments, graphite, food products, glass frits, rubber products, and cellulosic products. Both of these types of mills use a combination of compression and attrition forces to reduce particle size.

No matter what type of grinding equipment is used, the grinding media choice will be affected by variables such as initial/final particle size ratio, hardness of media versus material, potential discoloration concerns, contamination, and cost for media replacement. Energy use in any of these types of equipment will follow a general curve as shown in Figure 15.14.

Energy use increases dramatically as smaller particle size is required.

There are some specific laws that define energy consumption depending upon the range of particle size reduction. The first of these is Kick's law for large particle size greater than 50 μm:

$$E = K_1 \ln\left(\frac{D_{\mathrm{pi}}}{D_{\mathrm{pf}}}\right)$$

where E is proportional to the energy requirement, K_1 is an empirical constant, D_{pi} is the starting particle size, and D_{pf} is the final desired particle size. The energy requirement is proportional to the log of the particle size reduction requirement. This equation is a restatement of the difficulty of achieving small particle size.

For finer particles in the 0.5–50 μm range, a slight different equation normally applies, known as Bond's law:

$$E = K_2\left(\frac{1}{\sqrt{D_{\mathrm{f}}}} - \frac{1}{\sqrt{D_{\mathrm{i}}}}\right)$$

For very fine particles less than 0.05 μm, the energy requirement is represented by

$$E = K_3\left(\frac{1}{D_{\mathrm{f}}} - \frac{1}{D_{\mathrm{i}}}\right)$$

General requirements and concerns about all size reduction equipment include the following:

1) Speed of operation of the equipment, in terms of not only energy but also noise requirements and safety concerns.
2) Spacing between mechanical components of the various machines as they affect throughput of the material and potential contamination of the product with metal from the machines.
3) Particle size distribution will also most likely change in addition to the average particle size. This will affect downstream processing and storage.
4) The input of energy in all such equipment will raise the temperature of the solids being processed. It is important to calculate an accurate energy balance, monitor temperatures, and take into account possible product decomposition.
5) In addition to chemical decomposition concerns, we must never forget the high potential for serious injuries around high-speed rotating equipment. Proper guards, lockouts, and procedures must be in place.

As with many chemical engineering unit operations we have discussed, there are overlapping choices in equipment. In Table 15.3, we see a summary of the various types of solids size reduction equipment and their capabilities and limitations.

Table 15.3 Guide to size reduction equipment selection.

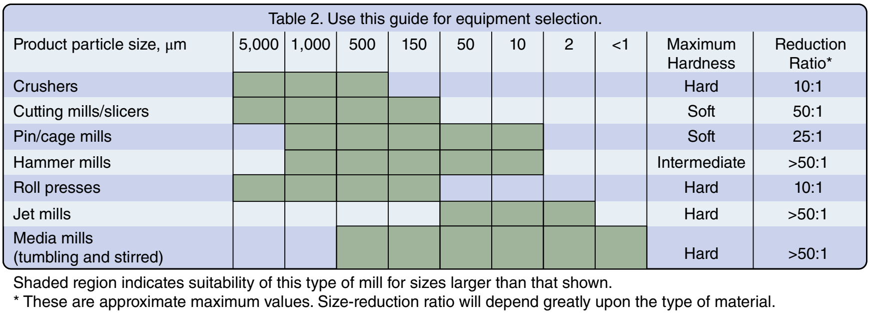

Table 2. Use this guide for equipment selection.

Product particle size, µm	5,000	1,000	500	150	50	10	2	<1	Maximum Hardness	Reduction Ratio*
Crushers	🟩	🟩	🟩						Hard	10:1
Cutting mills/slicers	🟩	🟩	🟩	🟩					Soft	50:1
Pin/cage mills		🟩	🟩	🟩	🟩	🟩			Soft	25:1
Hammer mills		🟩	🟩	🟩	🟩	🟩			Intermediate	>50:1
Roll presses	🟩	🟩	🟩	🟩					Hard	10:1
Jet mills					🟩	🟩	🟩		Hard	>50:1
Media mills (tumbling and stirred)			🟩	🟩	🟩	🟩	🟩	🟩	Hard	>50:1

Shaded region indicates suitability of this type of mill for sizes larger than that shown.
* These are approximate maximum values. Size-reduction ratio will depend greatly upon the type of material.

Source: Chemical Engineering Progress, 4/16, pp. 48–55. Reproduced with permission of American Institute of Chemical Engineers.

As we can see, the hardness, the initial particle size, and the relative size reduction required are all important variables in choosing the optimum equipment. A number of vendor trials are normally necessary.

Cyclones

Frequently, in handling solids and transferring them via the various processes discussed, there will be a reduction in particle size in that process, and if a gas stream is used, it is often not allowed nor economical to discharge this stream into the atmosphere. Some type of dust collection system may be required.

The most common is a cyclone, no different in principle to the newer cyclonic vacuum machines used for home cleaning today. The gas stream is impinged against the inner wall of a cyclonic device, and the solids collected are sorted at the bottom discharge. A typical example is shown in Figure 15.15.

Many times, the inside of the cyclone contains a bag to prevent particle discharge, similar to a home vacuum cleaner.

From a practical standpoint, this kind of equipment is ideal in that there are no moving parts, except for a possible discharge or sealing device at the bottom. However, they have their limits (as do all types of process equipment). Their collection efficiency is based on the logarithmic difference in particle size they are able to collect, as shown in Figure 15.16.

To avoid unwanted discharge of solids into the atmosphere or downstream of the scrubbing device, it is critical to know where this “breakpoint” is on performance and operate well to the right of it as seen in Figure 15.16.

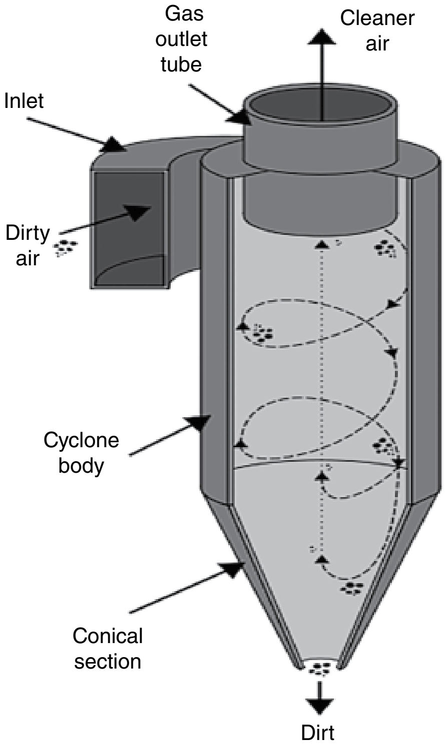

Figure 15.15 Dust cyclone. Source: By end:User:Cburnett [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons.

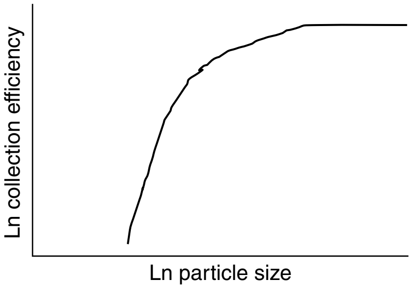

Figure 15.16 Cyclone collection efficiency versus particle size.

Screening

Once dried solids have been produced, it still may be necessary to screen them to isolate certain fractions by particle size and particle size distribution. This unit operation is frequently referred to as sieving, especially if its function is to recover particular solids sizes for use or sale. Solids size fractions are frequently expressed as “mesh size.” Table 15.4 lists some of the conversions.

Table 15.4 Mesh and size conversion and examples.

US Standard	Space between wires		
Sieve mesh no.	**Inches**	**Microns**	**Typical material**
14	0.056	1400	
28	0.028	700	Beach sand
60	0.0098	250	Fine sand
100	0.0059	150	
200	0.0030	74	Portland cement
325	0.0017	44	Silt
400	0.0015	37	Plant pollen

Screeners use vibratory or centrifugal force to separate materials. The rate of solids handling and separation will be affected by:

1) Particle size and particle size distribution
2) Difference between screen hole size and the solids size/distribution
3) Vibratory speed
4) "Friability" of the solids (tendency to break up when subjected to force)

They can also be either batch or continuous operations.

Since vibratory screens involve the use of mechanical energy, their components will be subject to wear, and the screen elements will need to be inspected regularly to ensure there is no degradation in the screen hole size.

Hoppers and Bins

Once a solid material has been transported, separated, and classified, it is normally stored in a bin or silo prior to being loaded into hopper cars, bulk sacks, or other solids shipping containers. At the other end, the receiving customer must also be able unload and transport the solid material into their usable storage.

There are several key design and operational variables in the design of hoppers and bins for solids:

1) Solids Density. As opposed to liquids and gases, which have fixed densities if pressure and temperature are known, we characterize solids density in two ways. *Bulk density* would refer to the density (i.e., $\#/\text{ft}^3$ or ρ_B) of the solids upon loading into a vessel. *Tapped density* (ρ_T) would refer to the density after the material has been "vibrated" or "shaken." This density will

always be greater, and we see this phenomenon in our daily lives when we open a cereal box. The box is rarely full. It was most likely full when it was filled at the factory, but the contents settle during handling and transport. The ratio of the tapped density to the bulk density is called the *Hausner ratio* and would be $\rho T/\rho B$.

2) Shear Strength. This is a measure of the solid's ability to "stick to itself" or an inverse measure of how difficult it is to "shear" the solids into smaller particles. The reason this is important in the solids area is that, in the process of flowing and moving, solids are subjected to forces and these can cause solids to degrade and decrease in size. A material's resistance to shear would be expressed as force per unit area or $\#/\mathrm{ft}^2$, in a direction parallel to the solid's surface. The higher this number, the less likely it is that a solid will degrade into smaller particles when being transported or moved.
3) Tensile Strength. This refers to a solid's resistance to force perpendicular to its surface (think about tearing a sheet of paper). If this number is low, the solids will have more of a tendency to break apart when subjected to mechanical impact. This is an important parameter when considering how much a particle will degrade as it passes through transport devices.
4) Jenike Shear Strength. After solids are transferred to a hopper by a conveying system, their ability to be removed from the hopper or silo depends not only upon the previous variables but also upon the shear strength between the solids and the hopper or silo wall material. If a solid has a strong adhesion to the wall material, there will be a tendency for the solids to "hang up" along the wall and produce nonuniform flow out of the hopper, with solids in the middle of the hopper flowing out the discharge faster than those clinging to the walls.

One of the simple physical tests frequently done on a solid is to measure its "angle of repose," as illustrated in Figure 15.17.

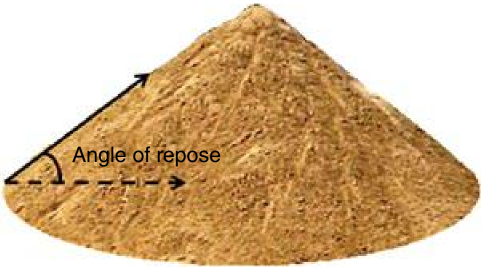

Figure 15.17 Angle of repose of a solid material. Source: Captain Sprite, https://commons.wikimedia.org/wiki/File:Angleofrepose.png. Used under CC BY-SA 2.5 https://creativecommons.org/licenses/by-sa/2.5/deed.en. © Wikipedia.

The stronger the adhesion forces between the solid particles, the steeper this angle will be. We can observe this at home by simply observing the angle formed from a batch of sugar versus a batch of flour dumped on a kitchen surface. It is important to take into account the atmospheric conditions in measuring these variables. Humidity can affect many of these variables.

If these variables are not all taken into account, we can see any or all of the following results in an industrial setting:

1) No Flow. If the wall adhesion and cohesive strength of the solids is sufficient, these forces may be greater than the gravitational force trying to flow the materials downward.
2) Erratic Flow. If these balancing forces are close, there may be conditions where the solids flow and stop erratically.
3) Nonuniform Flow. The balance of these forces may be such that solids do flow, but due to differences in particle size, the uniformity of what leaves the hopper may be quite different than what has entered the hopper.
4) Flooding. In an exaggerated condition of erratic flow, the solids, after having hung up in the hopper due to adhesive forces, may suddenly surge from the hopper when the force balance is suddenly overcome.

The angle of the metal at the hopper discharge will be an indirect indication of the angle of repose. The steeper this angle is, the more difficult it is to obtain flow of solids from the hopper. It is also likely that if a hopper has been improperly designed, we would see a sledge hammer at the bottom of the hopper to be used by operating personnel to “release” the solids hung up in the hopper.

Solids Mixing

It is sometimes desired to blend and mix solids entering a silo or hopper storage system or to mix solids being discharged from several hoppers. In these cases, it is critical that the properties of the actual solids mixture be used to design the transfer equipment and not to mathematically average what we think the individual properties are. This kind of mixing can be done with multiple-screw conveyor systems or a vertical cone mixing system.

Some of the key points are summarized as follows:

1) Solids are unique from the standpoint of chemical engineering in that their properties and processability and handling depend on more than their chemical formula. Variables such as particle size and particle size distribution are key variables that are not of concern when processing typical gases and liquids.
2) These unique solids properties are greatly affected by the equipment used to process, transfer, and store them. Mistakes are often made in designing or

specifying equipment based on the input to a solids handling device as opposed to the output from it.

3) There is little or no college education in this area, resulting in the majority of working and theoretical knowledge being in the hands of vendors and specialized consultants, both within companies and outside.
4) The flammability and fire hazards of solids are frequently not understood or ignored. Dust explosions can cause just as much damage and loss of human life as a petrochemical fire and explosion. Many types of solids handling equipment will input a great deal of energy into a solids system, requiring a thorough understanding of the heat balance associated with this heat input.
5) There tend to be a large number of equipment options for various types of solids processing and handling, requiring a thorough understanding of process and product requirements and the ability to make choices in an unbiased manner.

Solids and Coffee Brewing

Coffee grounds and beans are solids, so everything reviewed here is applicable, though not necessarily visible to the consumer. Beans are harvested from trees and need to be transported and stored. Then they are shipped to a coffee roasting (chemical reactor) operation. This may be the end of the journey as they are packaged into vacuum bags (to slow down the chemical flavor degradation) and shipped to a warehouse and ultimately to the grocery store shelf.

The beans are more usually ground and packaged into vacuum bags or cans (same reason) and then the same journey to the warehouse and grocery store shelf. The handling of large quantities of ground coffee will involve virtually all of the solids transport and storage unit operations we have discussed. The degree to which the particle size is reduced will determine whether the coffee grounds are classified as "perc," "drip," or "espresso." The finer the particle, the more surface area available for the water to contact in the brewing process and the stronger the taste of the coffee brewed. Many fussy coffee brewers will grind the beans at the last minute to minimize the surface area available for oxidation degradation (kinetics and reaction engineering).

Discussion Questions

1 To what degree are solids handling important in your processes? Raw materials? Intermediates? Final products?

2 Are all the appropriate information on the various solids known? How do they affect the design of solids handling equipment?

3 Are any of your customers complaining about caked products in drums or hopper cars that cannot be easily emptied? Why is this a problem? Is this a new phenomenon? If so, what changed?

4 If your customer were to request a different dryness of product, would you know how to produce it? The cost of doing so? What new types of equipment might be evaluated?

Review Questions (Answers in Appendix with Explanations)

1 The energy used in particle size reduction is primarily a function of:
A __Price of energy
B __Ratio of incoming particle size to exiting particle size
C __Size of the hammers or pulverizers
D __Strength of the operator running the equipment

2 Cyclones have primarily one very positive design feature and one very negative design feature:
A __No moving parts and sharp cutoff in particle separation
B __No motor and low particle collection
C __Can be made in the farm belt but cannot collect large size corn cobs
D __Are small and can make a lot of noise

3 A key solids characteristic in assessing solids cohesion is:
A __Particle size
B __Height of solids pile
C __Slope of laziness
D __Angle of repose

4 A poorly designed hopper can cause:
A __No flow when the bottom valve is opened
B __Segregated particle size flow
C __Surges in flow behavior
D __All of the above

Additional Resources

Note: Due to the unique nature of solids handling equipment, several videos are listed at the end of this resources list to allow visualization of the working of some of the equipment discussed. Some of these videos are

commercially produced. Neither the author, AIChE, nor Wiley endorses any of the particular equipment demonstrated.

Alamzad, H. (2001) "Prevent Premature Screen Breakage in Circular Vibratory Separators" *Chemical Engineering Progress*, 5, pp. 78–79.

Armstrong, B.; Brockbank, K. and Clayton, J. (2014) "Understanding the Effects of Moisture on Solids Behavior" *Chemical Engineering Progress*, 10, pp. 25–30.

Carson, J.; Troxel, T. and Bengston, K. E. (2008) "Successfully Scale Up Solids Handling" *Chemical Engineering Progress*, 4, pp. 33–40.

Maynard, E. (2012) "Avoid Bulk Solids Segregation Problems" *Chemical Engineering Progress*, 4, pp. 35–39.

Mehos, G. (2016) "Prevent Caking of Bulk Solids" *Chemical Engineering Progress*, 4, pp. 48–55.

Mehos, G. and Maynard, E. (2009) "Handle Bulk Solids Safely and Effectively" *Chemical Engineering Progress*, 09, pp. 38–42.

Zalosh, R.; Grossel, S.; Kahn, R. and Sliva, D. (2005) "Safely Handle Powdered Solids" *Chemical Engineering Progress*, 12, pp. 22–30.

Videos of Solids Handling Equipment

https://www.youtube.com/watch?v=WFE-vPXxxXc (accessed August 27, 2016).
https://www.youtube.com/watch?v=g7DdLLPknDo (accessed August 27, 2016).
https://www.youtube.com/watch?v=TdIq4WR50jQ (accessed August 27, 2016).
https://www.youtube.com/watch?v=L6sgGXXYdEU (accessed August 27, 2016).