Chapter 2
Dry Mixing

Mixing of powders is a very common unit operation in many industries, including food processing. Oddly, it is rarely discussed in undergraduate engineering classes and is not a common subject of academic research. Nonetheless, it is at the heart of many food plants either to produce an end product, such as dry soup mix, or to make an intermediate material, such as a topical seasoning for snacks (Clark 2005a, 2007).

There are many choices for mixing equipment, including horizontal and vertical agitated chambers, tumbling vessels, and air agitated operations. Mixing can be continuous or batch, but delivering the components and removing the product are often more critical than the choice of mixing equipment.

Some of the key issues in solids mixing are as follows:

- material handling,
- proper mix time,
- mixer volume,
- scheduling and surge,
- segregation, and
- feeding, especially in the case of continuous mixing.

Material handling. This refers to the delivery, scaling, and conveying of various components of a mixture, typically solids such as flour, sugar, salt, or other ingredients. Most formulas have major, minor, and micro ingredients, distinguished by their relative amounts in the formula. The dividing points are matters of judgment, but one approach is to say that amounts >10% are major, 1–10% minor, and <1% micro ingredients. Micro ingredients, while occurring in relatively small amounts, are often critical to the functionality of the final mix, as they may be vital nutrients, leavening agents, colors, or flavors. Thus, their proper dispersion in the mix may be especially crucial.

Each category of ingredient may be delivered in a different way. For example, major ingredients are often delivered in bulk, unloaded pneumatically into bins, and delivered to a mixer by pressure or vacuum pneumatic lines. Pneumatic transfer refers to conveying solids in pipes or tubes by suspending the solid particles in moving air. Depending on the concentration of solids in air, the transfer may be considered dense phase or dilute phase.

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Mix time. Mixing is a case where more is not necessarily better. There is usually an optimal mix time, which must be determined experimentally. The experiment is tedious because mixing is determined by measuring the standard deviation of some critical component. This requires taking multiple samples, at least ten, from various parts of the mixer at a succession of times. Often, mixing times are determined by using an easy-to-analyze component, such as salt, but care must be taken that the results apply to the material of most interest, since it may have different particle size and density than salt does. If mix time is determined on small-scale equipment, scale-up parameters can be established by using similar geometric ratios and keeping the Froude number constant. The Froude number is a dimensionless group equal to N^2D/g, where N is rotational speed, D is a characteristic dimension of the mixer such as diameter, and g is the acceleration due to gravity, all in consistent units. The implication of this approach is that as a mixer of the same geometric ratio, such as length to diameter, gets larger (i.e., the diameter gets larger), the required rotational speed is reduced to keep the Froude number constant. The resulting mix time in a larger mixer might actually increase because the intention is to keep the number of turnovers Nt, where t is the mix time, constant (Valentas et al. 1991).

Rotation speed also matters and usually has an optimum value. At too low a speed, there is inadequate agitation; but at low speeds, avalanching flow can occur, which is efficient in mixing. At too high a speed, centrifugal force sends all the particles to the perimeter. The Froude number is the relevant scaling parameter:

$$F_r = N^2D\big/g \tag{2.1}$$

where

N is rotation speed, s^{-1}
D is radius of cylinder (or another characteristic dimension of the equipment), mg is acceleration of gravity, m/s^2
$F_r = 1$ defines the beginning of centrifuging, so values considerably less than 1 are needed for mixing (e.g., 0.03).

Once a process study has been performed, it is important to control mix times because excessive mixing can promote segregation. Furthermore, unless all subsequent steps are carefully designed, a uniform mix can become segregated just by falling through chutes or filling bins.

Mixer volume. Most solids mixers have working volumes equal to 50% of their total volume. This means, for instance, that a ribbon or paddle blender should only be filled to just above its shaft. Other designs, such as tumblers and V-blenders, likewise must be only partially filled. This can be a source of friction between operators who want to maximize batch sizes and developers who understand the limitations of the equipment. If a mixer is overfilled, it is difficult for the solids to be moved by the agitator and mixing will be poor at best. Net production is actually improved by using equipment properly because mix times will be shorter and quality higher, resulting in less rework.

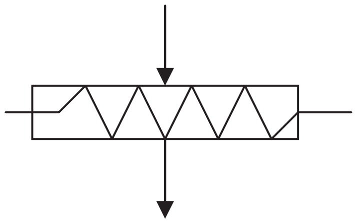

Fig. 2.1 Simple mixer (symbol for mixer with feed and discharge)

Scheduling and surge. The simplest mixing process consists of loading directly into a mixer, mixing for the correct time, and then dumping directly into packages or processing further. This requires some elevation of the mixer to allow room for packaging or conveying under the equipment. Often, there is a work platform on which bagged ingredients are placed and an operator manually loads the mixer. The mixer is idle during loading and unloading (Fig. 2.1).

A modest improvement in cycle time is achieved by delivering some ingredients in bulk to a receiver and scale, but this requires more head room and additional equipment (Fig. 2.2).

The next level of complexity adds a receiving bin, into which the components of a formula are loaded, manually through a bag dump station or pneumatically, while the previous batch is being mixed. The mixer is idle during unloading but is loaded quickly from the receiving bin once it is empty. The assumption is that successive batches of the same formula or of compatible formulas are being made. If cleaning is required between batches, then that time is added to the cycle (Fig. 2.3).

An obvious further improvement is to add a holding bin after the mixer. Now the mixer has minimal idle time, so production throughput, all other things being equal, is maximized. However, there is a price in both space and capital cost. Because solids transfers rely on gravity, this configuration is vertical and may not fit in an existing building (Fig. 2.4).

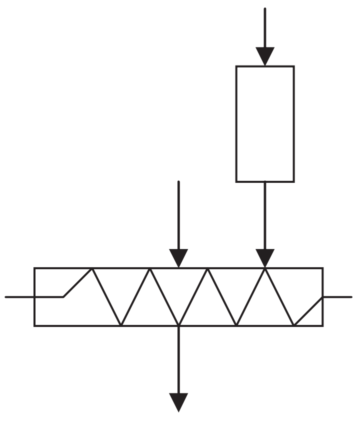

Fig. 2.2 Mixer with feed bin and direct feed

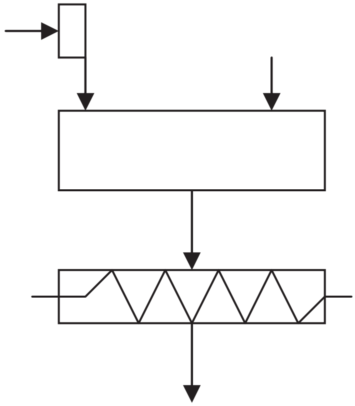

Fig. 2.3 Mixer with feed surge bin

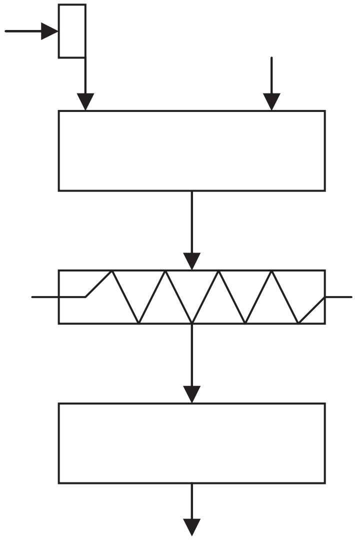

Fig. 2.4 Mixer with feed and discharge surge bins

A common arrangement is to have bag dumps and controls at ground level, but a work platform is still needed for cleaning and maintenance. In at least one instance, where packaging of a dry-mix consumer product was proposed to be increased, the addition of receiving bins was suggested to enable an existing mixer to keep up. It already had a holding bin for mixed product.

Segregation. For simplicity, most research on segregation and mixing is performed with binary mixtures that differ in size or density, but rarely both. For example, identical grains of sand may be dyed two colors. Or same-size spheres of steel and glass may be used.

A common mechanism for academic study is a rotating cylinder, which resembles the equipment often used for coating particles or making cement. Sometimes the cylinder is very thin, so it is considered two dimensional, which permits visualization of the patterns. Long cylinders in which puzzling alternating stripes of segregated particles can appear have also been studied.

The most common explanation for the patterns noted in some studies is that the angle of repose of different particles can differ, causing differential velocities along the axis of the tube. However, this is still considered an open issue, as particles with very different angles of repose may not segregate under some conditions. (The angle of repose is the angle that a poured heap of particles forms with a horizontal plane and is a characteristic property of a collection of particles.) Under the right conditions, small particles accumulate in the core and then "break through" to the surface, forming bands. If this were to occur in a process, the output of the rotating cylinder would vary in composition.

Theory and experiment have been used to identify some practical consequences. For instance, a non-cylindrical shape, such as an equilateral triangle, may be a better mixer than a cylinder. The degree of fill is a significant variable, with relatively low values performing better. This means that an operator who tries to force larger quantities through a given piece of equipment may be promoting poor mixing.

Another useful finding concerning rotating cylinders is that symmetric baffling makes little difference. Such baffling is common in coating drums. It is better to have just one baffle.

Real mixing situations often involve multiple components, which may differ in size and density. Some may be fragile and subject to breakage. Coatings or other components may be liquids, such as fat or water. Liquids can dramatically change the behavior of solids by forming liquid bridges among particles and changing their cohesiveness. If particles are close in density, reducing size and making all particles similar in size normally improves mixing. However, density and size have opposite effects, so where density may differ, size differences may help to compensate for what otherwise might be a segregating situation.

Cohesiveness refers to the ability of powders to stick together. It can be experienced qualitatively by pressing a small sample between one's fingers. It can be measured in a shear cell, where a sample is compressed and the force needed to slide the two halves of the cell apart is measured.

Cohesive powders can experience flow problems because it is easy for them to form bridges, but they are less inclined toward segregation than non-cohesive powders. Thus, in any specific mixing situation, the geometry, the composition of the mixture, and the potential effect of additives must all be considered. In general, properties of solids are not studied in industry to the same extent that properties of liquids are.

Relatively simple studies, such as measuring angle of repose, or "mixability" in a standard device, could be useful to industrial practitioners. One such device that has been used is a rotating sphere whose axis can also be oscillated. Depending on the frequency and amplitude of oscillation, segregation may or may not occur in binary mixtures. This or another simple system might be used as a standard instrument to study powder mixtures, much as a capillary tube is used to measure viscosity of liquids.

Feeding. Finally, if a proposed mixture must have widely disparate particles, such as croutons in a seasoning mix for stuffing, or the confection called bridge mix, it might be most practical to avoid conventional mixing altogether and just assemble the product in the package. This then becomes a feeding challenge instead of a mixing operation. Feeding is also the critical factor in continuous mixing.

2.1 Continuous Mixing

Continuous mixing occurs when separate streams of ingredients are combined in some device, mixed, and the mixture removed continuously. The device may be a ribbon or paddle mixer in which the feed enters at one end and is withdrawn at the far end or it may be a rotating tube with baffles or V-turns. In any case, the accuracy and reliability of the feeders is the key to success. Some feeders are volumetric while others rely on scales or load cells to continuously weigh a flowing stream. Weigh belt feeders need some positive control over the flow of solids. Some try to control flow by changing the speed of a belt conveyor, but for many solids the range of control by this method is limited. It is better to use the weigh belt as a measurement while running at constant speed and to adjust flow with the speed of a star wheel or screw feeder.

Volumetric feeders can be sufficiently accurate alone when the bulk density of a material is constant, but the bulk density of many solids changes with aeration, compaction, and moisture adsorption. Vibratory feeders are trays fed by slide gates, which control the flow of solids by changing the amplitude and frequency of vibration. Other solids feeders rely on using the angle of repose at rest to stop flow and initiating flow by inducing motion. These rely on the angle of repose being constant, which rarely is true for real materials.

An important consideration for solids feeders is the range of their operation, the ease of cleaning if they are used on more than one material, and their durability in service. The drives and clearances of feeders are usually chosen for specific materials. If the bulk density changes among materials used with the same device, the drive motor may prove inadequate or be oversized. There is a huge difference, for instance, in the density of cheese powder and salt, so that the same feeder does not work well on both materials.

Likewise, the screw design on a screw feeder may be specific for a given density and may not be sufficiently strong if the density increases. Finally, many solids are abrasive and can cause excessive wear if clearances are too tight in screw or star wheel feeders.

2.2 Addition of Liquids

Liquids are added to solids mixtures because they are components of the product, such as fat in dry soup mixes; to control dust by adhering fine particles to larger ones; and to improve uniformity of mixes by agglomerating fine particles of micro ingredients to larger particles. Liquids may be oils, water, or volatile solvents that are later evaporated. In all cases it is important that the liquids be well dispersed. There have been situations where liquids were added by simply pouring from a bucket or pumping from a hose. This is not likely to give uniform mixtures.

It is better to spray liquids from nozzles designed to give a mist of the specific liquid. Liquids can cause solids to build up on walls and agitators of mixers, so it is important that the liquid be added over a length of time and that it be sprayed onto the solids. One proprietary mixer specifically designed to incorporate liquids into solids, such as molasses into animal feeds, uses a slowly rotating cylinder with lifting fixtures that create a curtain of falling solids under a spray nozzle. Other mixers, such as tumbling V-shaped vessels, have a rapidly spinning dispersion bar for adding liquids and breaking up lumps that may form.

2.3 Specific Mixers

It is common to mix many materials in ribbon blenders – half-cylinder vessels with a horizontal shaft around which is wound one or two helical bands or ribbons. Sometimes the agitator consists of paddles on short arms attached to the horizontal shaft. In either case, the objective is to cause convective mixing by moving portions of the mixture around the vessel.

A well-known machine is an enclosed cylinder, which has plows attached to a horizontal shaft. The plows clear material from the side of the cylinder and circulate it back to the center. In addition, choppers – four-bladed agitators inserted between the plow paths, each with its own drive – disperse clumps that may form from liquid addition. Such mixers are used for encapsulation, adding lecithin to dispersible drink mixes, coating particles, granulation (where particles are deliberately grown in size, usually to make material for tableting), and many other purposes, including evaporation and drying.

The vertical shaft, orbiting mixer is a much-lower-shear machine in which an auger extends along the edge of a conical vessel and rotates about its own axis while it circles the vessel. The effect is to gently lift material without causing damage to fragile particles. These machines can be used as mixers or as holding vessels, to reduce or counteract segregation. They can be difficult to empty completely because the exit port is along one side. Also, if the shaft requires a bottom bearing, wear on the bearing can be high because it is immersed in the powder. Smaller machines do not need a bottom bearing.

Ribbon blenders are less expensive than vertical cone screw blenders. Ribbon blenders also use less headroom but have a bigger footprint. The vertical cone screw blender uses less power than a ribbon blender. Both types can have difficulty in completely emptying – the vertical cone because the exit is on the side and the ribbon or paddle because the bottom is level and the agitators must have some clearance from the shell.

Change-can mixers can handle very viscous materials with rotating agitators. The mixtures are held in a removable cylindrical vessel, which can then be transported to filling or further processing. Examples of materials made in such equipment include cosmetics, thick sauces, and high-solids concentrates.

2.4 Examples

1. A mixer with about 50 cubic feet of working volume is used to make a variety of dry powder consumer products that are packaged in pouches containing 8 oz each. The current packaging machine operates at 50 pouches/min. There is a holding bin beneath the mixer that can hold two mixer volumes. The ingredients are supplied in 50 lb bags, but because of partial weighs, i.e., less than 50 lb amounts in the formula, there are about 40 actions required of the operator to assemble a complete formula – dumping a bag or scooping a partial bag. Each action takes about 30 s, so it takes about 20 min to assemble a formula. Mix time is 15 min and it takes about 5 min to dump to the hold bin. The owner wanted to double packaging rate and wondered if mixing can keep up. Bulk density of the average formula is 30 lb/CF.

   Packaging consumes 25 lb/min at 100% efficiency and 22.4 lb/min at 90%. Double is 50 or 45 lb/min. The current system is reasonably in balance but would not keep up with a higher packaging rate. Possible solutions are

   - only increase packaging by 67%,
   - test to see if a shorter mixing time is sufficient (many mix times are arbitrary and may be too long or too short), and
   - add a feed bin to hold a mixer load of ingredients so loading ingredients can occur while the mixer is processing the previous batch.

   Adding a bin was recommended if space was available. Ideally, the bin would be overhead and would be filled through a bag dump station at grade. Head room was tight in this particular case, so the bin would be offset and unloaded through a horizontal screw conveyor.
2. Most commercial operators of dry mixers overfill their equipment. In one case, operators had, on their own initiative, increased recipe quantities until their ribbon mixer was so full that they had to force the lid closed. Not coincidently, the owner had received complaints from customers about inconsistent product – a food flavor. The owner was advised to reduce the formula quantity so that the mixer was about 60% full and the problem with consistency was resolved.
3. Another blender of dry spices also was overfilling and was advised to reduce from 87 to 60% of the volume. This required recalculation of the recipe and adjustment to make assembling convenient. As an exercise, recalculate the formula, given the following data and understanding that final volume can safely range between 55 and 65% of the total. Bulk density of the mix is 37 lb/CF and total volume of the machine is 64 CF.

   What would be some criteria for convenience? One approach would be the number of actions to deliver a given weight, where an action is dumping a complete package of an ingredient or scooping and weighing a portion of a package. Maximizing throughput would be another approach, within the constraints given. Typically mix time does not change significantly with load as long as there is sufficient room for the mix to move.

Ingredient	% Weight	Package size, lb
A	52	Bulk bags
B	27	50
C	7	22
D	5	11
E	4	20
F	3	15
G	2	15

4. A manufacturer of food ingredients used a continuous V-blender to make a wide range of products from about 12 different ingredients with different flow properties using weigh belts to control the composition. The only real control on solids flow was the gate opening on the storage bins. Some solids flooded while others periodically bridged and stopped flow, at which point the weigh belts would speed up fruitlessly. There was also a poor practice of repeatedly changing the calibration on the weigh belts. It was difficult to change the design, but a better approach would have been to replace the simple slide gates with positive feeders linked to the weigh belts. One typically cannot reduce the flow of free-flowing solids, such as soy flour, by reducing the speed of a belt. The flour will simply overflow the belt and its enclosure until the mechanism jams. I learned to be very skeptical of claims to control flow with weigh belts. I believe they are good measuring devices but not control devices.
5. Solids feeding is a complex topic. As previously mentioned, there are positive feeders, including star wheels and screw feeders. There are various gates and valves, which may be adjustable, so that the flow area is varied, but this can be difficult in some solids, so gates and slide valves are normally opened all the way or to a predetermined position, and not used to control flow. Often a gate from a bin is combined with some form of flow stimulation, including vibrators on the bin side wall and air injection through nozzles in the walls.

Solid powders often need stimulation to flow – when at rest they stay at rest. Advantage is taken of this property in a flow control device that looks like a Venetian blind. The angle of the slats is chosen so that the solids in the bin will not normally flow through the gaps because of the angle of repose. The device is vibrated when flow is desired, and the frequency of vibration can affect the rate of flow, because the angle of repose changes under vibration. One advantage of this device is that it does not require a horizontal offset, as do screws or vibratory trays.

Loss-in-weight feeders are bins with controllable discharge devices mounted on load cells so that their weight is continuously measured and the discharge device modulated to achieve a desired flow rate. The bin on a loss-in-weight feeder is usually fairly small to maximize accuracy and minimize cost. This means that it must be refilled, but during filling, the weighing function does not work. The discharge device runs at the last rate it was using, referred to as volumetric feeding.

Volumetric feeding can be accurate for solids with constant bulk density, but many solids change density under vibration, pressure, or aeration. Thus, the usual objective in designing a feeder is to minimize the time during which a loss-in-weight or gravimetric feeder is in volumetric mode. A target of 10–20% is common. This requires sizing of the feeder bin as well as the supply bin in relation to the target flow rate of solids, and the selection of a discharge device for the supply bin, which is normally installed above the feeder. The gravimetric feeder has instruments to measure high and low levels, calling for refill when the level is low and stopping refill when the high level is reached. The supply bin may be replenished by pneumatic lines or by dumping bags either directly into the bin or through a ground level bag dump station. The low level in the feeder bin must maintain a "heel" of solids so that flowing material does not just flow right through the open slats. To enable start-up, such feeders often are fitted with gates that close so that the heel can build up.

A system as described was created for a pet food plant in which fairly complex mixes were fed ultimately to a cooking extruder. The supply bins were arranged in a circle within a work platform. Each had a loss-in-weight feeder beneath, and these fed chutes to a bin for collection of the formula. As an exercise, specify the sizes of the supply bins and gravimetric feeders, given the following information:

Ingredient	% Weight	Bulk density, lb/CF
A	50	50
B	30	60
C	11	40
D	5	20
E	3	25
F	1	30

The desired total flow rate is 5,000 lb/h. (The formula and densities are arbitrary and do not necessarily represent a real product, but are used here for illustration.) To proceed, calculate volumetric flow rates and then pick working volumes of the feeders that will last for some length of time. (What should that time be?) Assume some replenishment flow rate. (How would you do that? The answer actually requires knowledge of the solids properties, which have not been provided. Some may aerate easily, some may be dusty or abrasive. For this exercise, assume a refill flow rate of 50 CF/min by gravity flow through a slide gate.) (Instructors can change the given parameters to get new versions of the exercise.)

One approach to this type of system is to fill the supply bins with a day's or a shift's requirements, hence the common name of "day bin." How big would they be if this were the approach? Another approach is to reduce capital by making the supply bins smaller and replenishing them either automatically or manually during the run. Consider the trade-off if labor costs \$15/h, one person can tend the system, and bins cost about \$5,000/m^3 with a scale factor of 0.45 (Maroulis and Saravacos 2008, p. 108). The scale factor is the exponent in the equation

$$C_2 = C_1 \left(V_2/V_1\right)^n \tag{2.2}$$

where

C_2 is cost of second vessel, \$
C_1 is cost of first vessel, \$ (use \$15,000 in this case)
V_2 is volume of second vessel, m^3
V_1 is volume of first vessel, m^3 (use 20 m^3).

The costs of many types of process equipment correlate with an equation of this form and often have exponents around 0.7. Corrections should be made for materials of construction and for inflation, which are being ignored here.

2.5 Some Lessons

1. In dry mixing, getting ingredients into the mixer and removing the mix in a timely manner can be as important as having the right mixer and mix time.
2. Provision of staging bins and surge bins can increase the productivity of a given mixer in a system, at the cost of additional equipment and space.
3. Most dry mixers are probably overfilled, so consistency can often be improved by reducing the batch size.
4. Optimum mix time is rarely determined for each formula. Rather it is usually arbitrarily chosen and is likely to be too long or too short. Determining mix time is tedious but worth doing.
5. Formulas can usually be modified to maximize the use of unit quantities of ingredients – whole boxes, drums, or bags.
6. Continuous mixing is a feeding problem, not a mixing problem.
7. Feeding solids has its own challenges, including measurement, flow control, wear from abrasion, and cleaning of complex equipment.

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