The Better Way to Mix Solids Into Liquids

The instinctive choice is in-tank mixing. But with problem powders, in-line mixing gives far better results

Stephen Russell-Hill
Quadro Engineering Inc.

Process engineers are often challenged with the proper selection of mixing technology for a given operation. While there is a wealth of published information on blending, solids suspension and gas dispersion, there is another class of mixing that is not well understood: the introduction of dry material or powders into water or other liquids. The frequent result is an incorrect application of mixing equipment.

Stored dry powdered materials, such as chemical reagents, rheology modifiers, fillers, abrasives or coloring agents, usually consist of aggregates and agglomerates, which must be dispersed in the liquid to produce "individual" entities. How effectively this is done has significant implications for the overall efficiency of a processing operation. For instance, incomplete powder wetting and dispersion can result in poor yields, unplanned filtration expenses, batch variations and excessive batch times. Tank cleanliness and cross contamination between batches can also be issues. A poorly designed mixing system represents a process bottleneck that can bring an operation to a halt.

Many such operating problems can be attributed to the conventional approach of using in-tank mixers, typically turbine or rotor-stator versions. The alternatives of selecting special mixer designs, or mixers that consume high horsepower per unit volume, lead to unnecessarily large capital expenditures and high operating costs. In most cases, single-pass in-line mixing is the better choice.

Challenges

The process engineer is fortunate if the solid material to be added is well behaved; that is, if the powders wet out and disperse readily. Such cases often can, in fact, be handled by in-tank mixing.

In practice, however, well-behaved solids represent only a small percentage of the applications in the process industries. The engineer is more likely to be confronted with difficult solids, a few examples being high-molecular-weight hydrocolloids, cellulose gums, starches, and proteins. Other examples are named below, in the context of the particular problems they cause.

When trying to mix difficult solids into liquids, two problems are particularly common:

- The powders float, resisting all efforts to "wet" them out, or
- They lump together, forming impenetrable sticky masses or "fisheyes" (lumps of product with a hydrated skin but a non-hydrated, dry core)

When powders float, it is usually due to surface tension effects. As a clump of powder is introduced to the liquid, surface tension forces can prevent the liquid from penetrating the clump. Under inadequate mixing, this unwetted clump can float on the liquid and have limited contact with it. When such material is added to the surface of an agitated tank, a floating mass, or "raft" forms (Figure 1) leading to buildup of solids on the wall and mixer shaft. These types of powders are often referred to as hydrophobic. Fumed silica, carbon black, cocoa powders and organic pigments are common examples.

The second, fish eye, problem arises with powders that are instead hydrophilic. When an agglomerate of hydrophilic powder comes into contact with water, the particles on the surface of the agglomerate become hydrated and swell quickly, crosslinking to form a tough, relatively impermeable gel layer. The particles inside of this outer layer cannot be hydrated because they are shielded from the water. At best, the result is small, transparent fisheyes (Figures 2 and 3), but more frequently it consists of lumps of various sizes.

Good examples of hydrophilic solids are the many powders classified as gums. These may be derived from a plant origin, such as locust bean or guar. Or, they can be either microbial in nature, such as xanthan, or synthetic, such as carboxymethylcellulose or other cellulose derivatives. Another class of hydrophilic powders that are difficult to wet and disperse consists of acrylic acid polymers (carbomers).

The conventional approach

As noted above, in-tank mixing, the option with which most processors approach the solids-into-liquids task, is suitable if powders wet easily and do not tend to form lumps. In these cases, the engineer need only concern himself or herself with providing enough agitation to suspend the solids, so that they will dissolve in the liquid, react with it or remain suspended, as the intended case may be. But, this approach leaves a lot to be desired if the powders are difficult, as defined earlier.

For one thing, the surface turbulence generated with conventional

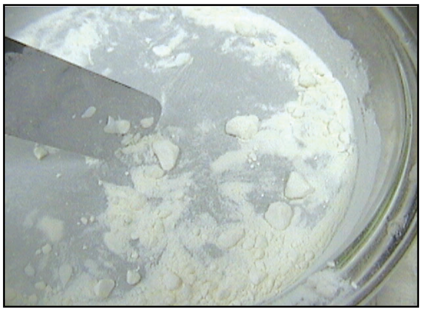
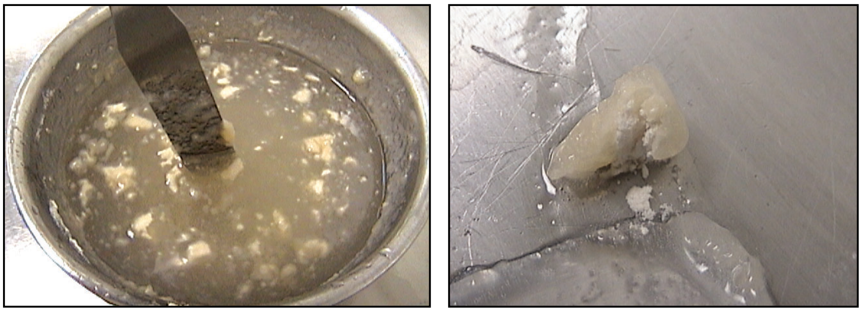


FIGURE 1. If not blended into liquids properly, hydrophobic powders may well float on the liquid surface as a 'raft'



FIGURES 2 and 3. As for powders that are hydrophilic, a characteristic problem with them is the formation of lumps of product with a hydrated skin but a non-hydrated dry core. The particles on the inside become shielded by that skin, and thus they cannot interact as desired with the liquid

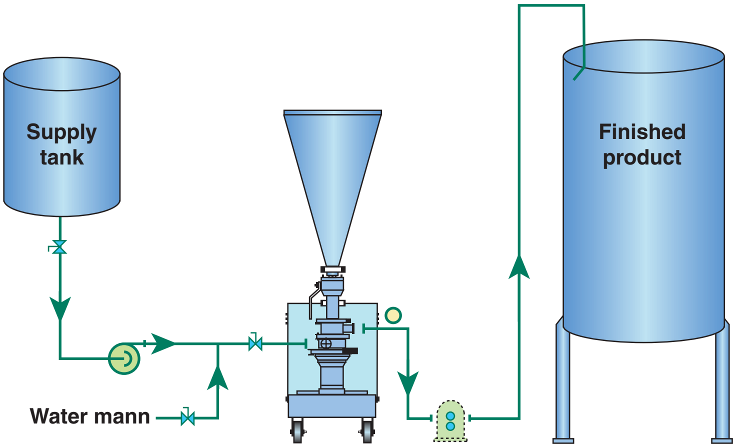


FIGURE 4. In this typical, batch in-line arrangement, the powder is introduced into the liquid at a point in the piping. The same solid-feeding principle can be applied during continuous processing

mixers is ordinarily not sufficient to draw in floating powders that have formed rafts. What's more, the presence of baffles leads to in additional solids buildup at the wall. Long batch times, powder buildup and subsequent waste during tank cleanup are the typical consequences. Cross-contamination of product can also be an issue if multiple formulations are processed through the same batch tank.

Some well-known strategies can be employed to help the mixing process along. For example, the baffles can be cut back or eliminated altogether, to promote swirl or vortexing. This tactic can be very effective at drawing in floating powders. However, significant air entrainment normally occurs as well, which requires the plant to add a sometimes lengthy deaeration step to the process.

A cutback or elimination of baffles also leads to increased radial flow patterns in the vessel, which can hinder blending and solids-suspension applications that require good top-to-bottom turnover. And, the hydraulic load acting upon the mixer shaft and bearings can increase significantly, leading to premature component failure.

If powder dispersion is the main challenge, it is common to use high-shear rotor-stator mixers, sometimes called homogenizers, which produce a greater shearing action with a relatively large invested horsepower per unit volume within the tank. But even though high-shear mixers, with high tip speed and tight clearance rotors and stators, are capable of high degrees of shearing action, there is an inherent problem with these devices when used in vessels: the maximum shear is found in the immediate area of the rotor-stator, whereas the local shear rates are lower throughout the rest of the vessel, effectively approaching zero towards the wall. The result is a distribution of shear in the vessel, with the particles not being treated equally. Some particles are subjected to intense shear, some see very little shear, and the majority see an average shear.

Because of this shear distribution in the tank and the unavoidably somewhat random arrival of lumps to the high-shear rotor-stator, it is not possible to accurately control the amount of shear applied. As a result, it is difficult to reproduce the desired process result from one batch to the next. These mixers also tend to generate significant radial movement in the vessel, which tends to cause vortexing and air entrainment, the consequences of which have already been highlighted.

To overcome the limitations with high-shear rotor-stator devices, most processors tend to run the mixer until they are satisfied with the dispersion or have eliminated most of the lumps. Apart from the obvious cost of long batch times, this overprocessing can potentially damage the end product if it is either shear- or heat-sensitive.

A classic case is the overprocessing of some acrylic-acid-polymer solutions that are commonly employed to increase viscosity in liquids. The dry material is extremely hydrophilic, and fisheyes form immediately in contact with water. As the lumps form, the batch is run longer and longer in an effort to eliminate them. However, the cross-linking polymers become shear-sensitive as they hydrate. As a result, the overprocessing reduces the effective viscosity. This, in turn, inspires the processor to compensate with the addition of yet more of the polymer, creating still more lumps. At the end of the batch, a significant amount of dry material must be removed by filtration, and thus wasted.

Another remedy consists of sprinkling the powder onto the moving liquid surface slowly, thus encouraging the particles to wet and hydrate "individually," lessening the formation of fisheyes. For most processors however, this approach is manual, slow and tedious. For example, three or more hours can be required to sprinkle, agitate, disperse and then hydrate a simple 250-gal batch of a carbomer ingredient for a hair-styling gel.

Depending upon the process and the nature of the powder ingredients, fisheye formation can be prevented by pre-wetting the powder in a non-aqueous solution, such as a glycol. Once dispersed, the solution is then blended into the aqueous phase to complete the hydration. This can be an effective approach; but it, too, represents an additional process step, extra equipment and added material costs.

In summary, high-shear rotor-stator mixers are designed to be shear producers, not flow producers. If blending and solids suspension are additional processing requirements in the vessel, then this style of mixer represents a poor selection, as do the conventional in-tank mixers.

A better choice

The issues summarized above can be addressed by in-line processing. It consists simply of adding the powder phase into the liquid phase at some point in the piping, not in the process vessel itself. Single-pass powder-addition device can be located in a pipeline between two vessels (Figure 4), in the water supply line leading to a batch tank, or at some point in a pipeline that is part of a continuous process. As an alternative to single-pass addition, the powder can be introduced into a recycle or recirculation loop that includes a tank.

Direct addition of powder to a process line has tangible advantages over in-tank mixing:

- No waiting for the wetting of floating powders
- No buildup on the tank wall, mixer shaft, and baffles. This reduces tank-cleaning time, lowers the chance for cross contamination, and virtually eliminates powder loss
- As there is no tank vortexing, significantly less air is entrained in the process fluid and, as a result, there is no need to install expensive deaerating devices or to wait for deaeration to occur

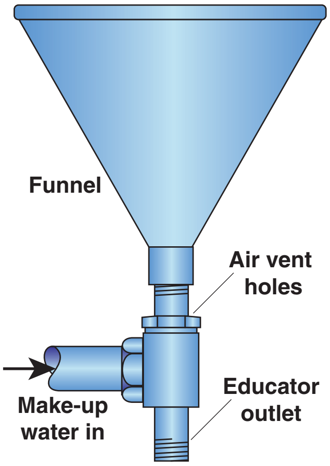


FIGURE 5 (above). The funnel-and-eductor system was the first system employed for in-line blending of powders into liquids

A single-pass, in-line approach allows for not only the controlled introduction of powders but also the controlled application of the shear necessary for the specific behavior characteristics of the powders. The controlled application of shear to the process fluid yields some significant benefits:

- There is repeatable processing from batch to batch
- Overprocessing to get rid of lumps is eliminated; this benefit is especially valuable when dealing with heat- or shear-sensitive products
- The applied energy is focused upon the task at hand – generating uniform, lump- and raft-free dispersions. No energy is wasted on trying to recirculate multiple passes of fluid through an in-tank dispersing mechanism (one application, for example, involving the dispersion of a 2,000-gal batch of gum, required 20–25-hp if carried out by an rotor-stator in-tank mixer, but only 7.5 hp if done via an in-line disperser)
- The performance of the dispersing device is independent of the characteristics of the dispersed product

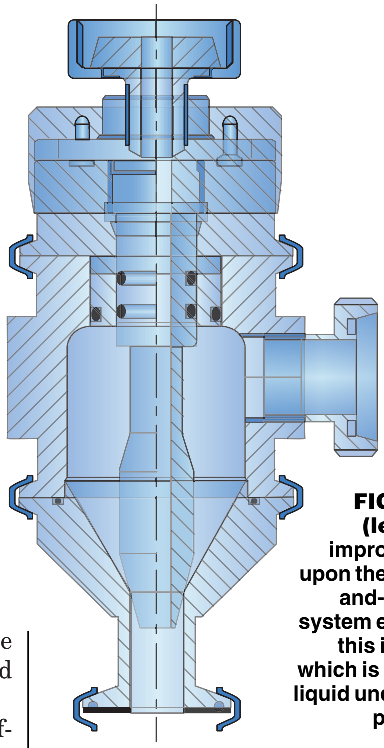


FIGURE 6 (left). An improvement upon the funnel-and-eductor system employs this injector, which is fed with liquid under high pressure

- Batch times are reduced

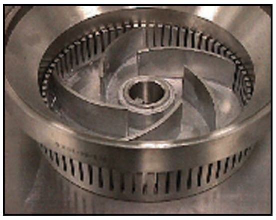
The in-line approach is also attractive because a single in-line device can feed a number of batch tanks. There is no need to provide a high-shear in-tank mixer for each process vessel. Furthermore, powders can be introduced and dispersed into the liquid during the filling of the vessel, thus reducing batch times.

In-line alternatives

A number of in-line technologies are available for processing solids into liquids. All can be used in a single-pass processing approach. However, each option has its particular characteristics that tend to limit the concentration or quality of dispersion that it can achieve with a given powder.

Regardless of equipment type, the powder becomes incorporated into the fluid because the device generates a vacuum. It is the rate at which this vacuum builds that dictates the powder incorporation rate. Dispersion occurs in a localized region of shearing, or where large velocity differences occur over relatively short distances.

Funnel-and-eductor arrangements: The simplest and oldest tool of adding powders into liquids in-line is



FIGURES 7 and 8. While high-shear mixing does not effectively mix difficult powders with liquid during in-tank mixing, the high-shear principle can be harnessed with good results for in-line blending

the powder funnel and eductor (Figure 5). The vacuum created due to a fluid flowing past an eductor draws the powder into the fluid.

This option features a simple construction with no moving parts, apart from the presence in many installations of a powder valve that separates the funnel from the eductor. The flowing powders begin to individualize as they are drawn down into the eductor.

However, powder incorporation rates are generally low with this option, as are the shear rates. The dispersing capability is limited, especially if one is dealing with hydrophilic powders. And the performance of the equipment is very sensitive to process upsets in flow rate, temperature, and viscosity.

Specialized eductors: More-sophisticated eductor systems have been developed that improve upon the basic capabilities of the funnel-and-eductor system described above. These devices incorporate a specially designed injector that is fed with the process liquid under high-pressure (Figure 6). As the liquid is forced through an annular orifice at high velocity, a powerful vacuum is created, and the liquid forms a spray or curtain. Meanwhile, in a separate stream, the solids are drawn under vacuum to the eductor. The solids are introduced into the spray or curtain, which wets and disperses them.

Due to the higher feed pressures and the nature of the eductor nozzle design, greater concentrations of solids can be introduced, and the powder agglomerates encounter greater shearing forces than they would in a typical funnel-and-eductor system. Drawbacks to this specialized-eductor approach include the need for higher-pressure feed pumps, a risk of vaporization and cavitation when operating with hot fluids, and the fact that it can be difficult to disperse high concentrations of difficult powders.

Pump-style blenders: Later variations of the powder funnel-eductor approach employ some form of rotating mechanical device to boost the ability to incorporate and disperse the powder into the liquid. One of the most common types is effectively a modified centrifugal pump with a powder funnel attachment, often referred to as a powder blender. With this device, liquid is pumped into a vertically mounted pump chamber that incorporates a centrifugal pump wheel, a perforated screen or set of baffles at the periphery of the impeller to help redirect flow and disperse powders, and a powder feed tube that keeps the powder agglomerates separate from the liquid phase until the last moment, when the impeller draws the powder and liquid phase together and discharges the blend through the screen or baffles. Vacuum is created by the action of the fluid being discharged from the unit. Some vendors offer two-stage models (with two pump impellers) that offer increased vacuum and, hence, a higher capacity for solids addition.

A valve on the powder funnel isolates the powder from the liquid prior to the blending operation. Some vendors recommend the further use of that valve to throttle the powder addition rate, in order to control the discharge consistency (for example, if the processor wants a low concentration). However, this strategy should be considered with care, because partial valve openings tend to result in a buildup of partially hydrated material in the powder feed tube, and can also lead to an increase in air entrainment in the product and a decline in the performance of the blender.

This equipment should always be used with a feed pump and liquid-flow control. Depending upon the discharge conditions (line length, bends, elevation, other considerations) a secondary discharge pump may be required to deliver the product to downstream processing.

In general, these pumpwheel-style devices are suitable for relatively high capacities and solids concentrations. On the other hand, they run into difficulties when dealing with gums and thickeners that are difficult to disperse; the shearing effect delivered by the pump impeller and screen is generally not sufficient to effectively disperse such powder agglomerates in single-pass processing. Recirculation can be attempted, but the changing physical properties of the dispersed product (such as an increase in viscosity) can cause the performance of the unit to quickly drop off.

Similarly, these devices cannot be used with high-viscosity liquids (above 250 cP), and are susceptible to problems, due to cavitation, when processing hot fluids. The possibilities of cavitation in the reactor head and vapor wetting of the feed-tube and powder-valve area can cause powder clumping and bridging.

High-shear blenders: Many vendors offer significant improvements over the original pumpwheel-style blender. Instead or relying upon a pump impeller and screen/baffle plate as the dispersing mechanism, designs have been introduced that incorporate more-aggressive dispersion tooling (Figures 7 and 8) with similarities to the aforementioned high-shear rotor-stator mixers for in-tank usage. With a design employing a vaned rotor and a slotted stator, or a toothed rotor-stator design, the operating clearances and tip speeds are such that the powder is subjected to intense shearing as it is introduced into the liquid phase and passes through the rotating element. The most challenging hydrophilic gums and polymers can readily be handled with these mechanical devices.

In some designs, the establishment of a "liquid ring" in the reactor head containing the rotating element, much like the configuration in a liquid-ring vacuum pump, generates the vacuum that is required to draw in powders. Other designs rely upon high-pressure flows past an eductor upstream of the dispersing mechanism as the motive force for powder incorporation.

Table 1 offers a summary comparison of the technologies available today for in-line mixing of solids into liquids. The table should be used solely as a general guideline; and the numbers shown for capacity and solids concentration are for relative comparison purposes only, and may vary depending upon the physical properties and other characteristics of the powder being handled.

TABLE 1. RELATIVE PERFORMANCE OF IN-LINE TECHNOLOGIES

Technology	Relative Capacity	Relative Shear	Typical Liquid Throughputs, lb/h	Typical Powder Concentrations, wt. percent
Funnel-and-eductor	Low	Low	250	<10
Specialized eductor	Moderate	Moderate	50,000	<25
Pump-style blender	High	Moderate	100,000	<35
High-shear blender	Moderate	High	50,000	<15

Most vendors of in-line devices are willing to help the engineer match the right device to the task, through a variety of testing programs, onsite demonstrations, monthly rentals and other means. For the engineer, the main goal is to end up with the best device for the job at hand, and to aim to achieve the desired mixing result in a single pass. ■

Edited by Nicholas P. Chopey

Author

Stephen Russell-Hill is general sales manager for mixing equipment at Quadro Engineering Inc. (613 Colby Drive, Waterloo, Ont. N2V 1A1, Canada; www.quadro.com). Previously, he was general manager, Flow Div., for Alfa Laval Canada, and product manager and application engineering manager for Prochem Mixing Equipment Co. He has 20 years of experience in industrial equipment sales and application engineering, with a focus on mixing. He is a member of AIChE, the Professional Engineers of Ontario and the North American Mixing Forum. A registered professional engineer in the Province of Ontario, he holds a bachelor of applied science degree in chemical engineering from the University of Waterloo.