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Don't Err with Air Compressors

Understand what's involved in getting a suitable supply of compressed air

By David M. McCulloh, Mac Consulting Services

CHEMICAL PLANTS vary widely in size and complexity — and so do the types of compressors used in them, and the compressors' capacity control systems. The units often differ significantly from those at most industrial manufacturing plants using compressed air, where the most common compressor now is the oil-injected rotary screw.

While chemical plants generally pose less variation in flow requirements from shift to shift than other manufacturing facilities, there can be differences in pressure requirements for the various processes, plus instrument air. Air quality requirements, including dryness, also may be stricter for some processes, requiring different drying and filtration methods. Each of these aspects may require segregation of some systems for more efficient operation. In addition, the cost of loss of production, due to an interruption of air supply, must be considered. We'll look at these considerations.

DEMAND PROFILE

It's essential to know how, where and in what quantities compressed air is being used. List each process or application, together with the minimum, average and peak rates of flow and any cycle times on and off. Staggering the timing of peak demands can reduce the total maximum demand. One common problem is that distribution piping is sized for the average demand, with pressure drop based on that. When peak demand is significantly higher, the pressure drop also will be significantly higher, resulting in a lower pressure at the point of use or requiring a higher discharge pressure from the compressor(s). So, size distribution piping for the peak flow rate with an air velocity in the pipe not to exceed 30 ft/sec.

Also, establish the required operating pressure for each process or application. Significant differences in required operating pressure may identify potential segregation of processes or applications for overall system efficiency. Operating the total compressed air supply at the highest required pressure results in increased power consumption (an approximately 1% increase for every 2 psi). Having a separate air supply at the required pressure for a specific process or application can improve overall system efficiency. In each case, ensure that sufficient backup air supply is available.

While adequate primary compressed air storage (near the compressors) is essential for efficient capacity control of the units, adequate secondary storage (near each point of use) can prevent wide swings of pressure at each point of use.

Compressed air leakage in the distribution system also contributes to the cost of operation. Leak detection equipment is readily available and an ongoing leak detection and repair program should be standard practice. In addition, idle production machines or processes should be fitted with shut-off valves that close upon shut down.

Adequate pressure sensing points must be available from compressor discharge, before and after dryers and filters and throughout the distribution system to each point of use. This can allow monitoring the dynamic variations in the entire system.

COMPRESSOR TYPES

Three kinds of compressors generally find use at chemical plants:

1. *Centrifugal*. Larger plants often use centrifugal compressors, which are capable of substantial flows of air, although they're now available in as low as 100 hp. These are dynamic compressors, where a continuous flow of air has its velocity increased by impellers rotating at high speeds. The velocity energy, or kinetic energy, is translated into pressure energy in diffuser or volute chambers. The number of impeller stages depends upon the desired final pressure and efficiency. Cooling occurs between each stage. An important advantage of centrifugal compressors is that they are inherently oil-free, with no lubricant coming into contact with the air passing through the compression process. They generally are water-cooled.

Centrifugal compressors have a characteristic pressure curve, where pressure increases as capacity decreases. This is an important consideration in capacity control, which is further complicated because pressure-head-making ability

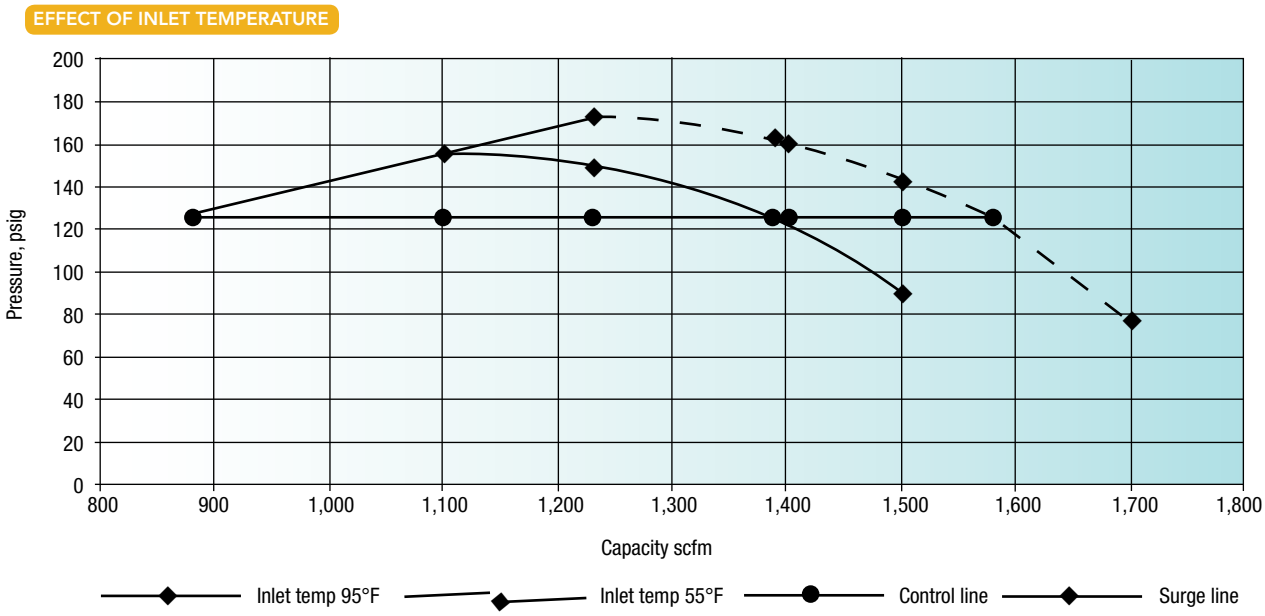

Figure 1. Reduced capacities in centrifugal compressors can lead to a reversal of flow.

varies inversely with absolute inlet temperature and resultant mass. This means that, when designed for a given inlet capacity in actual cubic feet per minute (acfm), the mass flow increases inversely with absolute inlet temperature and the pressure generated also increases because of the denser inlet air. So, for a given discharge pressure, the compressor will have "grown." See Figure 1, which presumes the same inlet temperature to each stage. Cooling water temperatures can further affect the curve. Figure 1 has a control pressure of 125 psig. It also shows a "surge" line, to the left of which, at reduced capacities, a flow reversal can occur and should be avoided.

Generally, plants want to maintain a relatively constant pressure to the system; controls will reduce capacity if the pressure tends to rise above the set point due to decreasing demand. With centrifugal compressors, a common means of capacity reduction is by progressively closing an inlet valve or guide vanes. This causes a pressure drop at the compressor inlet, reducing the mass flow in proportion to the absolute inlet pressure. Because inlet guide vanes impart rotation in a similar direction to the impeller, this provides energy savings compared with a simple butterfly valve. However, as stated, flow reduction must be limited to avoid surge and generally flow shouldn't go below 80% or 70% of capacity.

The biggest potential energy problem is when further capacity reduction requires opening a blow-off valve, discharging already compressed air to atmosphere. This should be avoided. Some centrifugal compressors can be unloaded at this point to keep from wasting compressed air. Some units also can be run in a load/unload mode. Unloading involves closing the inlet valve and discharging the substantially reduced minimum flow to atmosphere, resulting in an unloaded power of approximately 15%. The bearing designs must be capable of running in this markedly reduced mass-flow condition; any desired change in capacity control should be discussed with the manufacturer to avoid potential problems.

Advantages of centrifugal compressors include:

- oil-free air delivery;
- generally well packaged and no need for special foundations;
- relatively smooth air delivery; and
- relative first cost per cfm or hp improves with size.

Disadvantages include:

- limited constant discharge pressure capacity control range; and
- need for specialized bearings for high rotational speeds and monitoring of vibrations and internal clearances.

At full capacity and 100-psig discharge pressure, operating cost typically runs 16–20 kW/100 cfm.

2. *Rotary screw.* Many chemical processes require oil-free

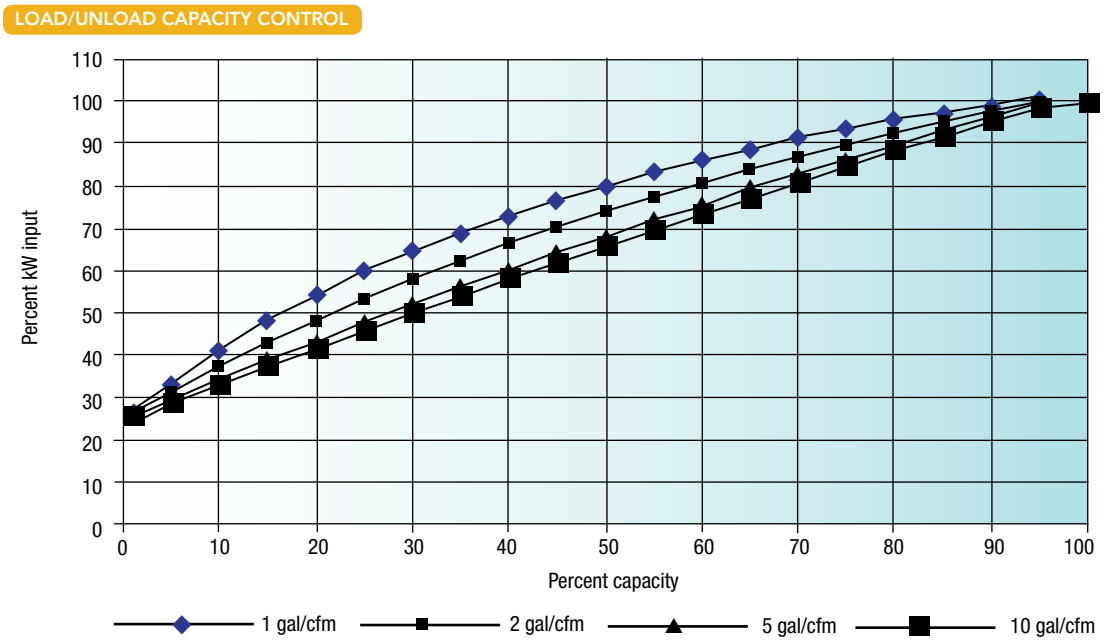

Figure 2. Oil-injected rotary screw compressors require ample capacity to avoid cycling with this type of control.

air, so oil-free compressors are popular. Oil-injected compressors sometimes are used with additional clean-up equipment including specialized filtration — but this adds pressure drop, mandating a higher compressor discharge pressure than otherwise would be needed.

The oil-free rotary screw compressor generally requires two stages of compression, with inter-cooling, for pressures in the 100–150 psig range. Capacity reduction on constant speed compressors by inlet valve throttling is limited to about 80% of capacity, due to increasing discharge temperature. Below this it's necessary to unload the compressor. Ample storage capacity then is required. Compressors with variable speed drive (VSD) provide more flexibility in capacity reduction.

Oil-injected rotary screw compressors can use various means of capacity control. The most common but least energy efficient is by inlet valve throttling. At about 40% of capacity, the power requirement is more than 80% of full load power. Below 40%, the compressor is unloaded, with no flow to the system, but will then require about 25% of full load power. Again, ample storage capacity is required. Load/unload (full capacity/zero capacity) control can cause excessive cycling unless ample storage capacity is provided (Figure 2).

Some models are available with variable displacement, which provides capacity control by changing the effective length of the rotors. This offers some improvement over inlet valve throttling but also is limited in the capacity control range.

VSD rotary screw compressors provide much more efficient capacity control, although they sacrifice a bit of efficiency at full capacity. Compare the percent power at various capacities (Figure 3), with the comparable data for inlet throttling (Figure 2).

For the oil-free rotary screw compressor, advantages include:

- complete compact package;
- relatively low first cost; and
- no need for a special foundation.

Disadvantages include:

- less efficiency than water-cooled reciprocating type; and
- higher long-term maintenance costs.

Its operating cost at full capacity and 100-psig discharge pressure runs 18–22 kW/100 cfm two-stage.

For the oil-injected unit, advantages include:

- complete compact package;
- relatively low first cost;
- no need for special foundation; and
- routine maintenance (oil, filter, separator changes).

Disadvantages include:

- less efficiency than water-cooled reciprocating type; and

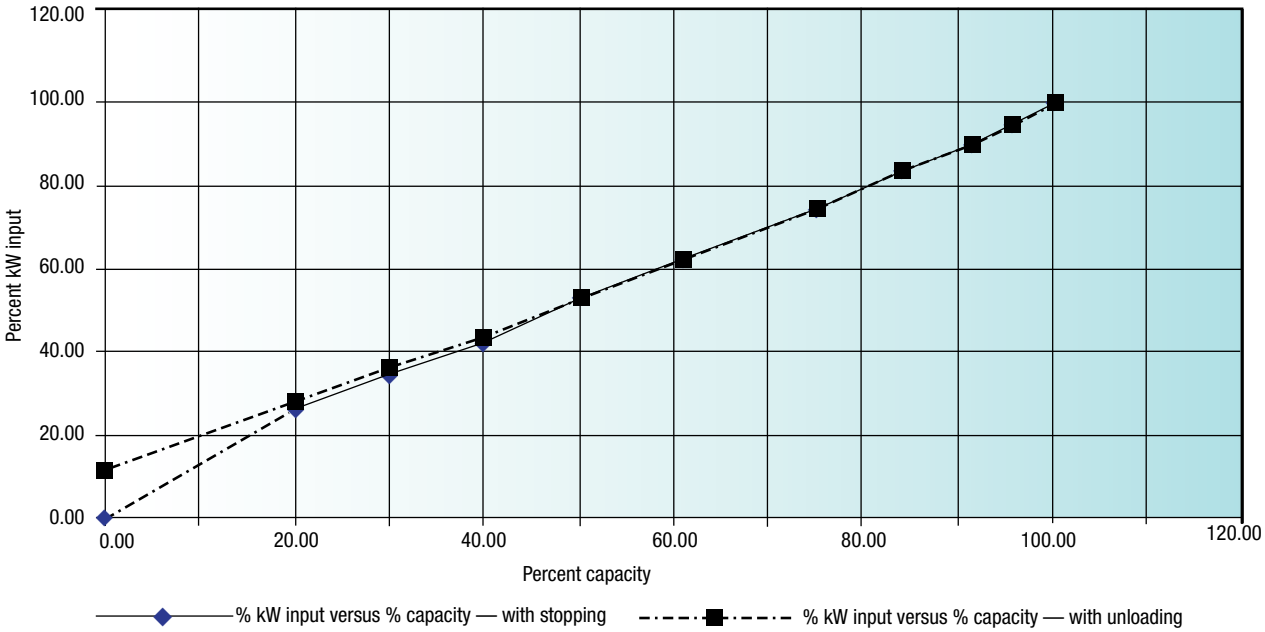

Figure 3. VSD oil-injected rotary screw compressor provides more efficient capacity control than possible with constant speed unit.

• potential problem of oil carryover.

Operating cost at full capacity and 100-psig discharge pressure runs 18–19 kW/100 cfm single stage and 16–17 kW/100 cfm two-stage.

3. *Reciprocating compressors.* These units come in single-acting and double-acting configurations. The single-acting type uses only one side of the piston to compress the air, whereas the double-acting uses both sides. Single-acting compressors generally are small in size, air-cooled, and limited in capacity and time of operation but can be conveniently located near the point of use.

Double-acting units usually are water-cooled and can have two or more stages of compression, which increases efficiency. They also can have multiple steps of capacity reduction, providing 100/75/50/25/0% capacity within a specified pressure control band. Both lubricated and non-lubricated piston/cylinder versions are available.

The advantages of double-acting compressors include:

• efficient compression;
• efficient multi-step capacity control; and
• relatively routine maintenance.

Disadvantages include:

• relatively high first cost;
• need for special foundations due to vibrations; and
• oil carryover on lubricated versions.

The operating cost at full capacity and 100-psig discharge pressure for a water-cooled double-acting unit runs 15–16 kW/100 cfm. In contrast, an air-cooled single-acting compressor runs 22–24 kW/100 cfm.

MULTIPLE COMPRESSORS

Many plants link together a number of compressors into a single compressed air system. In such a system, all compressors but one should be operated at full capacity and optimum efficiency. The one so-called trim compressor is capacity controlled to satisfy system demand at a relatively constant pressure. This also minimizes the amount of storage capacity required. Sophisticated sequencing control panels can allow a change of trim compressor to even out run time and changes where demand varies from shift to shift. The limited capacity control range of many centrifugal compressors restricts their capability as trim compressors. Constant-speed oil-free rotary compressors have similar limitations but those with VSD are capable of a wide range of capacity reduction. Oil-injected VSD rotary compressors also are available. VSD compressors can maintain a supply pressure within ±1 psi. (Centrifugal compressors don't come

with VSD because the pressure-head-making capability varies as the square of the rotating speed and the required discharge pressure can't be maintained at the reduced rotating speeds.)

Pressure/flow controllers also can be used to provide a relatively constant supply pressure (±1 psi) while demand varies but may require an increased compressor discharge pressure. Where used, they should be located downstream of the primary air dryers(s) and primary air receiver. The controller should be guaranteed by the supplier for operation over the entire anticipated range of rates of flow.

The same considerations apply to multiple compressors in different systems. The advantage of separated systems is that each can have its compressor(s) and compressed air treatment equipment tailored to the specific required conditions of operation without being influenced by the requirements of another system. One potential disadvantage is the need for adequate standby compressors and treatment equipment in each system. When systems are segregated to allow operation at different pressures, it's possible to arrange for supply from a higher pressure system to a lower pressure system in times of emergency — provided the higher pressure system is adequately sized.

AIR QUALITY

Whichever type of unit provides compressed air, it's crucial to ensure the quality of air suffices for its intended use. Process equipment manufacturers often note air quality requirements. Where this isn't given, ask the vendor to specify the necessary level, preferably with reference to a published standard. ISO 8573-1 is the International Standard for Air Quality Classes. It defines allowable levels of solid particles, moisture and liquid condensate, and lubricants. In some environments hydrocarbon gases can be ingested at the compressor inlet, so that the air delivered may not be truly oil-free and may require appropriate filtration.

A major consideration in many chemical plants is the quality of the product(s) being produced and the compressed air that comes in contact with it. As a general rule, air shouldn't be dried more than required for the given application. This avoids unnecessary operating and maintenance costs. However, the limitations of compressed air drying equipment should be understood.

Refrigerant-type dryers cool the air to allow condensate to be drained off but at 32°F freezing will occur, so drying is limited to a pressure dew point of 35°F to 38°F. While this is adequate for many industrial applications, it generally doesn't suffice for many chemical processes.

Standard regenerative-desiccant-type dryers use a material that adsorbs moisture and provide a pressure dew point of -40°F. Others are available down to -100°F. This type of dryer generally has twin towers, allowing one tower to be drying the compressed air going to the system while accumulated moisture is being removed from the desiccant in the other. Some dryers use heated purge air; a cooling option may be needed where processes are temperature sensitive. Specify a dew-point-sensing controller. A standby dryer allows for maintenance without shutting down the process.

In segregated systems, drying can be tailored to meet the specific needs of the system.

As with drying, filter only to the extent needed for the particular process. Use ISO 8573-1 to determine the appropriate classes. There are three basic types of filtration: particulate, coalescing and adsorption. Specific applications may require combinations of types.

One common problem is that filters may be sized to match the size of the piping in which they are to be installed. The anticipated system flow rate should match the recommended flow rate of the filter. Determine piping size not by the size of the filter connections but by the anticipated maximum system flow rate, with a pipe velocity not to exceed 30 ft/sec.

Locate filters where they can be readily serviced; arrange standby filters, with bypass valves, to allow continuous operation during maintenance.

Install a good differential pressure gauge across filters and take regular readings to establish trends for scheduled maintenance.

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Drying Compressed Air in Hazardous Atmospheres

David J. Connaughton, Parker Hannifin Corporation

IN MANY industries, the atmosphere, though safe to breath, may be unsafe for an electrical spark. These areas often have pneumatically operated equipment for safety. And that equipment needs a source of clean dry air or as it is called in the industry, Instrument Grade Air. Plants typically have a centralized instrument grade air line that delivers air to the instruments that need it. However, oftentimes the instrument grade air is of inferior quality and contaminated with water. This air will benefit from a point of use drying system that guarantees instrument grade air. Traditional drying systems using PSA (Pressure Swing Adsorption) or refrigerant require expensive modifications to operate within hazardous areas. Air dryers made from hollow fiber membranes can dry compressed air without the use of electricity and are therefore safe for hazardous environments.

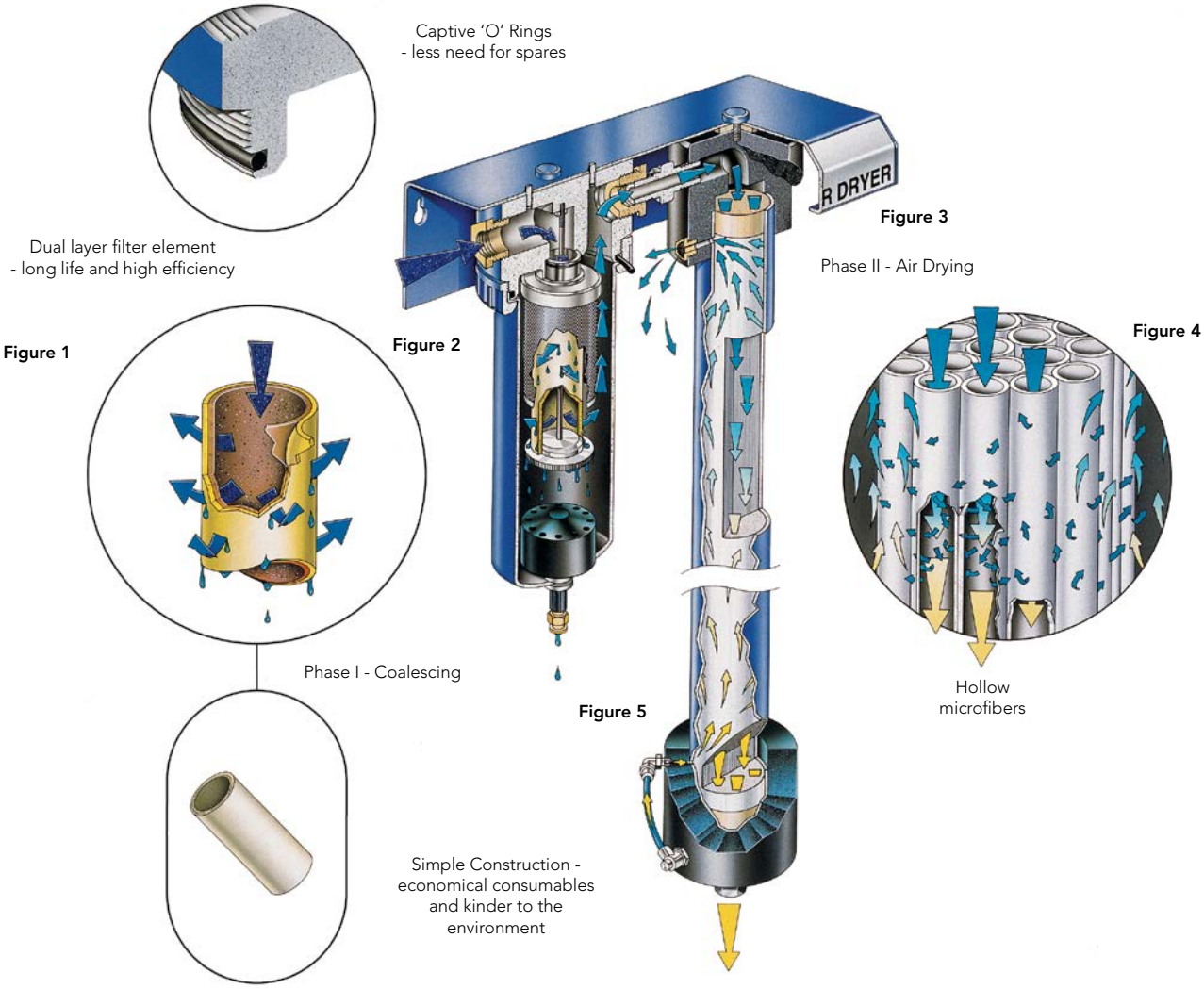
Hazardous locations have or could potentially have high concentrations of flammable gases, vapors, combustible dusts or ignitable fibers and flyings. Refineries, chemical processing plants, mines and grain mills are examples of industries with hazardous atmospheres. Even a small spark can lead to a horrific explosion dangerous to equipment and workers in the area.

The National Electric Code (NEC) goes into great detail to discuss hazardous location types. According to the NEC there are three types of hazardous areas. The first type is called Class I. Class I areas are areas where there may be flammable gases or vapors present at a concentration that would be explosive or ignitable. Here are some examples of Class I locations:

- Refineries
- Gas Storage and dispensing areas
- Dry cleaning plants
- Spray finishing areas
- Aircraft hangars and fuel servicing areas
- Utility gas plants
- Sites that store or handle LPG or natural gas

Areas where there are combustible dusts are called Class II by the NEC. Fine dusts, due to their large surface area, when suspended in air can cause as strong an

MEMBRANE AIR DRYER - PRINCIPAL OF OPERATION



explosion as one occurring at a refinery. Here are some examples of Class II locations:

- Flour mills
- Feed mills
- Grain elevators
- Plastic manufacturers
- Starch and candy producers
- Fireworks factories
- Spice, sugar and cocoa factories
- Coal and other carbon handling sites

The last category includes areas where there are easily combustible fibers or flyings present. These are called Class III. These fibers may not be suspended in the air, but rather can collect around equipment or light fixtures where they can be exposed to heat, hot metal or a spark to cause fire but are probably not explosive. Some Class III sites include:

- Textile and cotton mills
- Wood processing facilities
- Any processing sites that generate wood or combustible fibers

In addition, the NEC specifies the type of condition that the hazards can be present. The hazards may be present normally or abnormally. Normal conditions are called "Division 1" and abnormal are called "Division 2".

Further classification addresses the nature of the hazardous substances. These are called "Groups" and are a function of the ignition temperature, explosive pressure.

Group A is acetylene. Acetylene has extremely high explosive pressure and is the only material in this group.

Group B contains hydrogen and a few other materials.

Group C contains ether and Group D contains most hydrocarbons, fuels and solvents.

Dusts have their own groups starting with metal dusts as part of group E. Group F are carbon, coal and other dusts and Group G which contain flours, starches, grains and other explosive dusts.

Equipment located in hazardous areas must be specifically designed to prevent ignition and explosion. Electrical enclosures that are found on traditional compressed air drying equipment like PSA and refrigerated dryers must be strong enough to contain an explosion within the cabinet. Therefore the walls must be very thick and heavy. The internals in the cabinet must operate at temperatures below the ignition temperature of the hazardous material. Lastly, the cabinet must be designed such that any ignition inside the cabinet would not immediately exit the cabinet but rather the ignited gases would need to be quenched so that the escaping gases don't cause an explosion outside the cabinet. The added weight and heavy duty design increase the cost and size of traditional compressed air drying equipment. Fortunately there is an alternative.

Membrane air dryers, on the other hand, do not use electricity and are safe for any hazardous location whether it is Class I, Class II or Class III. Membrane air dryers have been commercially available for at least 20 years and have proven themselves in many hazardous locations. Prior to entering the membrane drying module, compressed air passes through a high efficiency coalescing filter to remove oil and water droplets and particulate contamination with an efficiency of 99.99%, The liquids are removed by the filter cartridge. They continuously drain from the filter cartridge to the bottom of the housing, where they are automatically emptied by the autodrain assembly (see Figure 1 and Figure 2). The air leaving the prefilter, therefore, is laden only with water vapor, which is then removed by the membrane module. The membrane module contains bundles of hollow fiber membranes that permeate only water vapor through the wall of the membrane. No oxygen, nitrogen or any other component of air permeates the membrane. Water on the outside surface of the membrane is evaporated by a sweep of low pressure dry air (see Figure 3 and Figure 4). The driving force that pushes the water vapor through the wall of the membrane is the difference in partial pressure of water inside the hollow fiber (high) to the partial pressure on the outside of the fiber wall. Therefore, drying of the compressed air is accomplished without the use of electricity.

For a given cubic foot capacity, membrane air dryers are lightweight and small. This is another advantage as space is at a premium in most industrial sites.

Membrane air dryers are also exempt from ATEX certification as they do not have enough energy to cause and ignition and the air movement is unlikely to produce static electric charges.

Drying compressed air at point of use is always a challenge. In the industries that have hazardous areas, selecting the safest, smallest and most cost effective dryer is critical. Based on cost, size, and safety, membrane air dryers are clearly the best choice.

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Optimize Humidity for Efficient Powder Handling

Too much or too little moisture can cause problems during processing and storage

By Jamie Clayton, Freeman Technology

THE INTRODUCTION of even relatively small amounts of moisture may transform a free-flowing powder into something far more difficult to handle. This well-recognized behavior reinforces the tendency to label moisture as always being detrimental to efficient powder handling. However, there are notable occasions when the introduction of water can have a positive effect. For example, in the process of wet granulation, the ability of moisture to promote adhesion between particles is highly beneficial, and leads to the production of free-flowing granules from cohesive fine powders. In certain systems water acts as an interparticle lubricant, thereby improving flow characteristics; in others it enhances conductivity, discharging the electrostatic forces of attraction between particles that otherwise would increase cohesivity.

So, understanding the effect of humidity on the material being handled and stored is essential for developing cost-effective operating strategies. Where moisture is a problem, steps usually can be taken to control it — e.g., maintaining a storage facility at lower humidity or drying a stream exiting a wet unit operation, such as crystallization or wet ball milling, before further processing. However, such strategies incur cost. Optimizing operation depends upon ensuring humidity levels are controlled adequately but not excessively; this, in turn, relies on knowing how easily the powder takes up water and, most importantly, the impact of that moisture on behavior.

CRUCIAL STARTING POINT

An understanding of powder flow characteristics is essential. They define how easily and reliably material will move through a plant but, beyond this, they directly influence the efficiency of important unit operations such as blending and vial/die filling. In many instances controlling powder flow behavior is the key to achieving manufacturing excellence.

The mechanisms of powder flow are complex. They are influenced by an array of different parameters; some relate to the particles' physical attributes, such as size and shape, and others, such as humidity, to the system itself. Although there is a general understanding of these individual mechanisms, the multitude of interactions that govern the specific behavior of a given powder prevent the prediction of flow properties from first principles. The pragmatic alternative is to measure powder properties that correlate with in-process performance and use knowledge of the mechanisms of powder flow to develop a consistent rationale for these observed behaviors.

When a powder flows the particles within it are moving relative to one another. The ease with which this happens is governed by the strength of interparticular forces that arise from friction, mechanical interlocking, adhesion/liquid bridges, cohesion and gravity. The interaction and relative magnitude of these forces dictate the behavior exhibited by a powder in any specific environment.

Frictional forces inhibit movement, either between particles or between particles and the walls of the confining vessel.

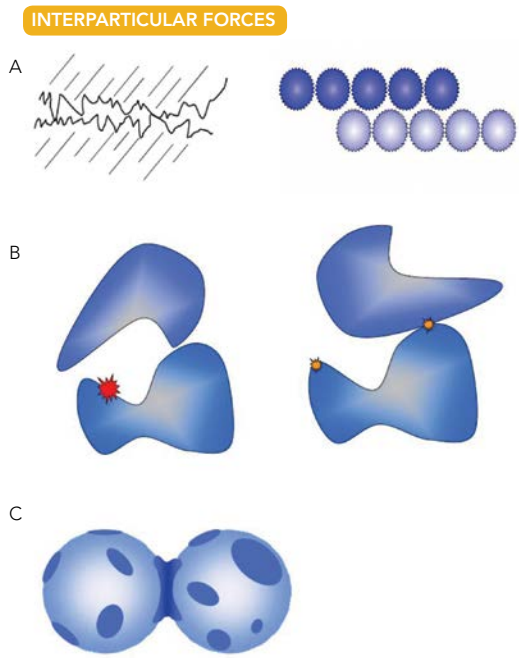

Figure 1. Frictional forces (a), mechanical interlocking (b) and liquid bridging (c) can impact particle movement.

Their strength is strongly influenced by surface roughness, with smoother particles and surfaces exerting less resistance to flow, all other factors being equal.

In contrast, mechanical interlocking is more closely correlated with overall particle shape. Irregular particles, if oriented in a certain way, may slot together like pieces of a jigsaw puzzle, significantly resisting further movement (Figure 1).

Liquid bridging often accounts for the negative impact that moisture can have on flow behavior. By bridging the gap between particles, or particles and the vessel wall, a liquid can increase adhesive forces and inhibit particle motion.

Cohesive forces, such as Van der Waals forces and electrostatics, tend to be especially important in defining the behavior of fine powders. Gravitational forces, on the other hand, have a much greater impact on systems containing large high-mass particles because the force imposed by gravity is function of mass.

POWDER ASSESSMENT

The complexities of powder behavior have led to the development of many alternative testing methods that seek to summarize this behavior in the form of just a single number. The diversity of these techniques underscores that many different approaches can provide some insight into powder behavior. However, processors are increasingly recognizing that reaching the levels of manufacturing performance now demanded requires a focus on methods that:

- are reliable and reproducible;
- generate process-relevant data that correlate with performance; and
- allow sensitive assessment of the impact of environmental variables such as moisture and degree of aeration.

Three techniques that score highly against these criteria and have proven especially relevant for process-related studies are shear, bulk and dynamic property measurement.

Shear analysis, which was developed in the 1960s [1], is particularly useful for hopper design and, more generally, for characterizing consolidated, cohesive powders. Modern instrumentation with well-defined methodologies and a high degree of automation has brought enhanced reproducibility and reliability, ensuring the place of shear analysis in the modern powder testing toolkit.

DYNAMIC TESTING

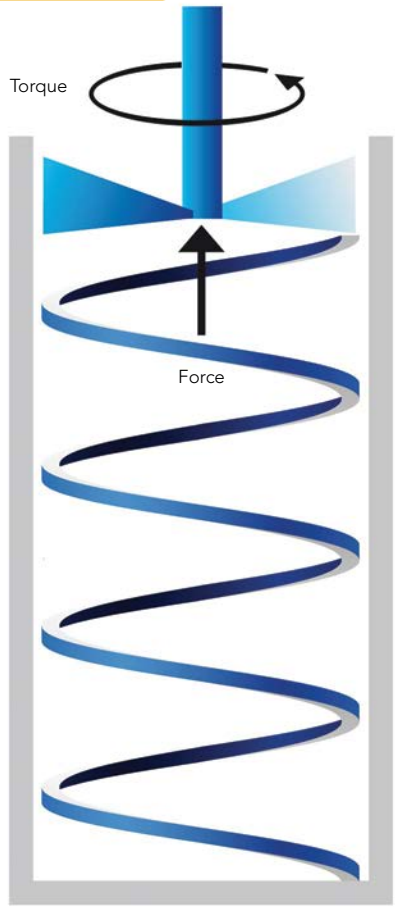

Figure 2. Powder can be subjected to different stress regimes by rotating the blade upward or downward, and air can be introduced for measuring aerated energy.

MOISTURE TAKEUP

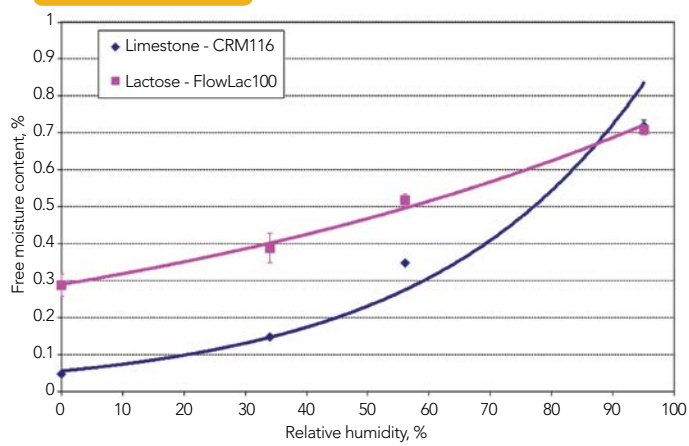

Figure 3. Both test materials take up relatively low levels of water even when exposed to high humidity.

Bulk property measurement, i.e., the determination of bulk density, permeability and compressibility, though well-established, similarly has benefited from instrument refinement. Bulk property data may be used directly in process design calculations and provide a general insight into powder behavior that supports the prediction of performance in certain processes.

Dynamic powder testing methods, which were developed in the late 1990s, marked a step change in powder characterization, rather than refinement of an existing technique. Dynamic characterization involves measuring the axial and rotational forces acting on a blade as it traverses through a sample along a fixed helical path to generate a value for flow energy (Figure 2). This value directly quantifies powder flowability, i.e., the ease with which the powder flows. The technique is highly sensitive and has the distinct advantage of allowing powders to be characterized in a consolidated, conditioned, aerated or even fluidized state. It can directly measure the response of a powder to the introduction or release of air.

Let's now look at how shear, bulk and dynamic property measurement can provide insights on the impact of humidity on two different, industrially relevant powders.

THE IMPACT OF HUMIDITY

We assessed the impact of humidity on limestone (BCR116, a very fine material with a mean particle size of four microns, used as the standard reference powder for shear testing) and lactose (FlowLac100, an example of a widely used pharmaceutical excipient, which has a mean particle size of 140 microns).

First, we allowed samples to equilibrate in environments of varying relative humidity to assess how much water was taken up. For both materials, absorption and adsorption rates are quite low (Figure 3). However, the more interesting question for processors is whether the resulting moisture content of the powder can change behavior. To answer this question, we subjected each sample to shear, bulk and dynamic property testing using the FT4 Powder Rheometer. Reference 2 provides full details of the test methodologies.

Limestone. The dynamic measurements for limestone

LIMESTONE RESULTS

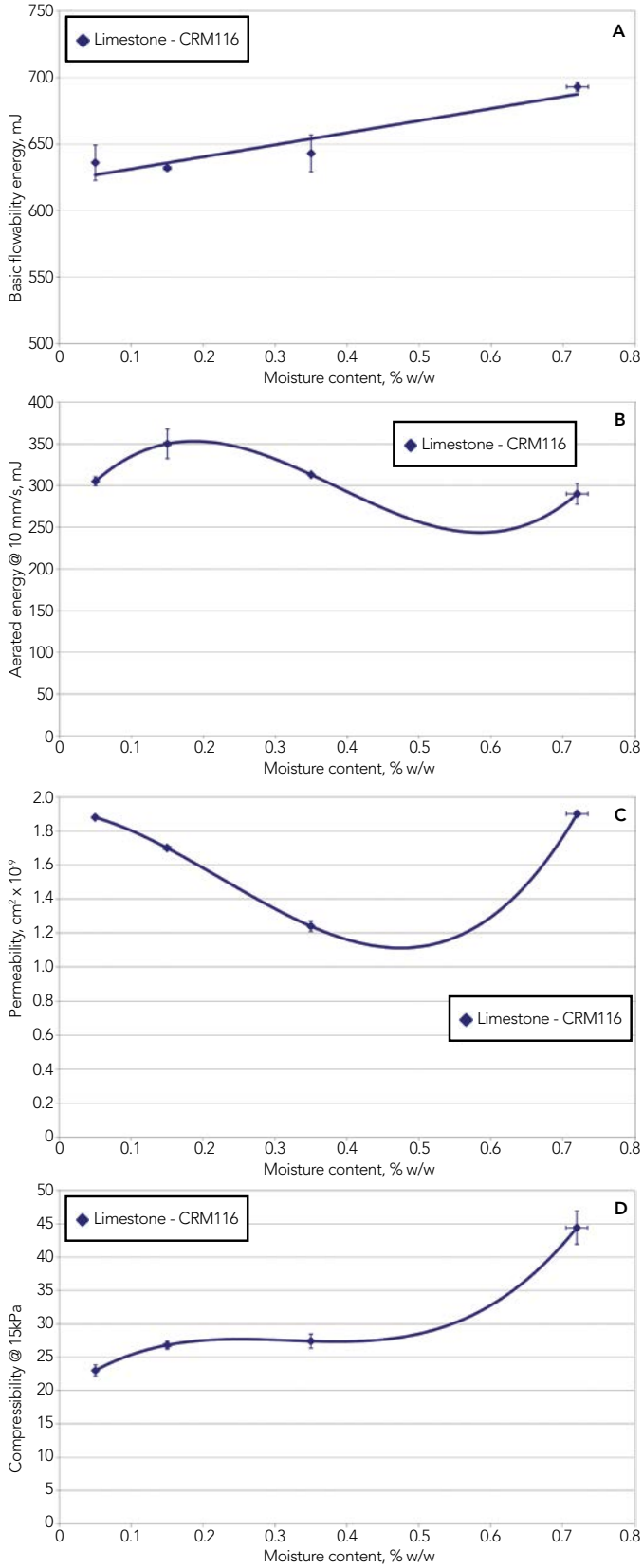

Figure 4. Data demonstrate the impact of moisture on dynamic (BFE and AE) and bulk (permeability and compressibility) properties.

show that basic flowability energy (BFE) — the ease with which the powder flows under forcing, compacting conditions — increases with increasing moisture content (Figure 4a). This behavior may indicate the water acts as a binder, producing liquid bonds that raise the overall cohesivity/adhesivity of the system and promote the formation of loose agglomerates. The variations observed in the aerated energy (AE) data (Figure 4b) at first sight would seem contradictory to the BFE results. However, these are better understood when studied alongside the permeability results (Figure 4c), which are generated by measuring the pressure drop across the powder bed for a given air flow — higher pressure drop equates to lower permeability.

The limestone has very low permeability across all levels of moisture content, largely because of its fine particle size. In general, the strength of interparticle forces increases with decreasing particle size; this is why finer materials tend to have relatively high cohesivity. Strong interparticle forces result in a packing structure that resists the passage of air, causing low permeability. So, with cohesive powders the inclusion of water provides relatively little scope to reduce permeability further. This effect is illustrated clearly here, where increasing moisture content minimally changes permeability in absolute terms.

For analogous reasons, the limestone substantially resists aeration; any upward-flowing air tends to channel through to the surface rather than promoting steady fluidization. Therefore, the introduction of air has a limited and variable impact on flow energy, with the extent and influence of the channelling varying erratically with moisture content.

The compressibility data (Figure 4d) support the hypothesis that increasing cohesivity explains the trend in BFE. Cohesive powders have a tendency to trap air within them, making them relatively easy to compress. In contrast, less cohesive powders have particles that are efficiently packed together; compression is difficult because there's significantly less air to expel. Therefore, the increase in compressibility as moisture content goes up points to steadily rising cohesivity. The bulk density of the

LACTOSE DATA

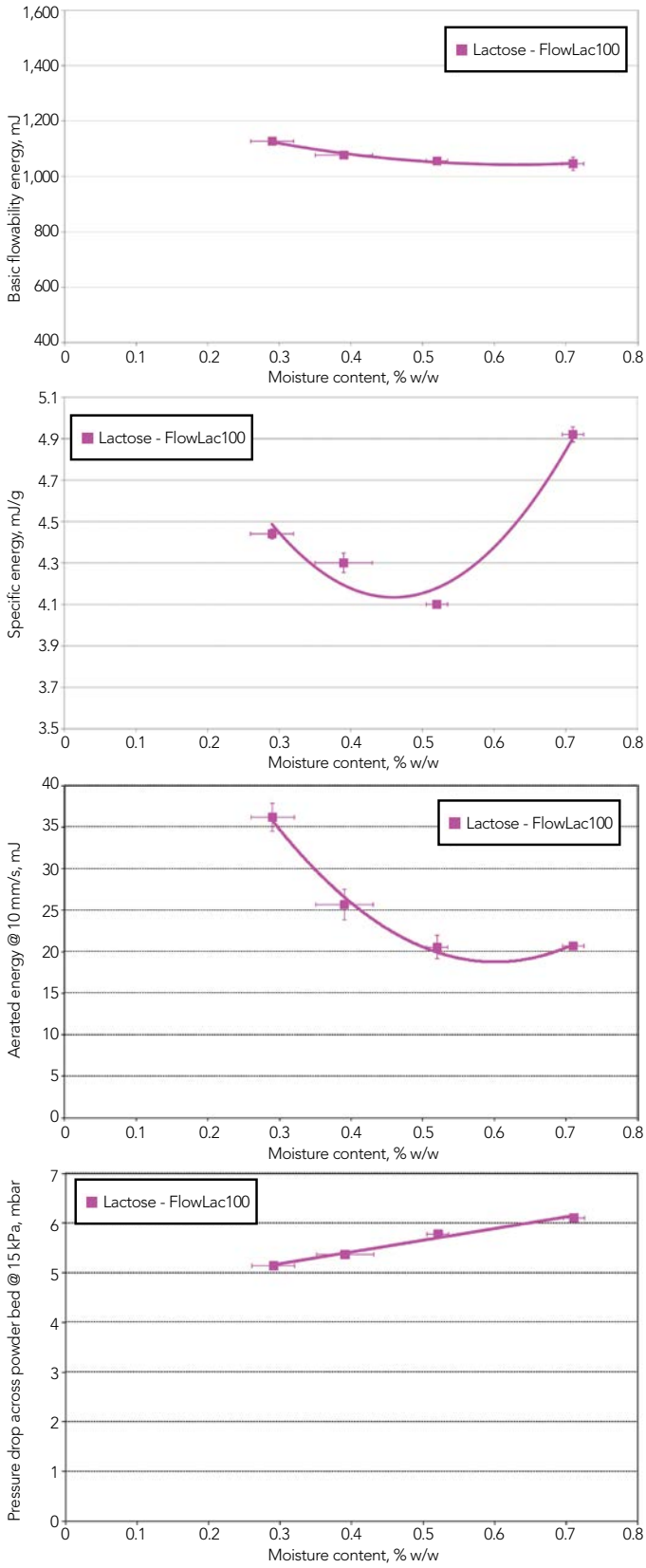

Figure 5. Results show the effect of moisture on dynamic (BFE, SE and AE) and bulk (permeability) properties.

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limestone also decreases with increasing moisture content (data not shown), which supports the idea that higher cohesivity leads to more air trapped within the bed.

In this instance, bulk and dynamic property testing identified some significant effects but shear analysis provided little differentiation between the samples. This observation underlines the value of multifacted powder characterization and the greater sensitivity of certain powder testing techniques for specific applications.

Lactose. The very different behavior of the lactose is immediately obvious from the BFE data (Figure 5). The lactose shows a fall in BFE with increasing moisture levels, suggesting that here the presence of water actually may lubricate interparticular interactions. However, the specific energy (SE) data for lactose show the opposite effect: SE rising with increasing moisture content. This interesting behavior highlights an important, industrially relevant issue — namely, the processing environment strongly influences powder flow behavior. The BFE testing regime subjects the powder to a compacting action that is more representative of the forced-flow conditions that would apply, e.g., during extrusion or the pushing of powder into a partially filled die. In contrast, the upward motion of the blade during SE testing subjects the powder to a gentle, lifting action that produces values that reflect the unconfined flow behavior that would be observed when a powder pours freely from or into a vessel.

As with the limestone, the presence of moisture very likely will produce liquid bridges that would tend to increase the cohesivity of the system. This fits with the observed trend in SE. However, the BFE data suggest that under forcing conditions this effect is more than offset by a competing lubricating mechanism that makes interparticular movement easier. Therefore, under compacting conditions the net impact of the moisture is beneficial. AE values also decrease with increasing moisture content, suggesting that here too, water reduces the strength of cohesive bonds.

Evaluating bulk properties (Figure 5), the permeability data are perhaps most revealing. The steady rise in pressure drop observed indicates the powder becomes less permeable to the flow of air as moisture content increases. This supports the view that liquid bridges form within the system, inhibiting the passage of air. In contrast, both compressibility and bulk density (data not shown) change very little as a function of moisture content. The variation in bulk density (only 2 to 3 % across the experimental conditions) is particularly noteworthy because it suggests that in this instance bulk density/packing changes aren't responsible for the observed trends in flowability (as quantified by the dynamic test data). This indicates that powder testing methods based on bulk density could easily fail to detect the changes in behavior induced by moisture. Shear analysis is similarly insensitive for the lactose as for the limestone.

BETTER PROCESSING

The effective management of humidity to ensure optimized processing relies on understanding and quantifying the effect of moisture in a way that's relevant to the process. Experimental data presented here for limestone and lactose illustrate the very different responses that moisture can induce and highlight the insight provided by multifaceted powder characterization, most especially incorporating dynamic measurement.

The results demonstrate that even for materials that exhibit low moisture uptake, exposure to humidity levels typical of an industrial environment can significantly affect performance. Furthermore, they provide evidence dispelling the idea that moisture always degrades powder behavior. For example, under certain conditions moisture improves the flow properties of lactose, a result attributed to the lubrication of interparticular movement.

As many processors already recognize, moisture's effects are neither linear nor predictable. So, it's essential to apply appropriate powder testing strategies to build a secure basis for intelligent decision-making around design and operation. Achieving the highest levels of manufacturing excellence and profitability requires keeping powders just dry enough to ensure optimal processing. Relevant powder testing provides the information needed to achieve this goal.

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