Hammer Milling and Jet Milling Fundamentals

Gary Liu, P.E.
DuPont

Select the optimal hammer mill or jet mill for your application by characterizing the feed material and conducting milling tests.

Size reduction, or comminution, by mechanical crushing and grinding is an important unit operation in the chemical, power, mineral, metallurgical, and pharmaceutical industries. Throughput for an individual device can range in scale from a few kilograms per hour for specialty products to hundreds of tons per hour for ore-extraction operations. It is estimated that size reduction accounts for approximately 5% of global energy consumption.

Many sources *(1–4)* describe the fundamentals of material size reduction, but few teach you how to select and size the right type of mill, how to operate your mill efficiently, and how to maintain your mill.

There are numerous types of grinding mills. This article focuses on two widely used types: the hammer mill and the jet mill. Hammer mills are often used for general-purpose grinding and the finished product particle size ranges from millimeters to tens of microns. The jet mill is primarily used for superfine grinding applications and creates particles sizes down to a few microns. Understanding the fundamentals of each mill's respective grinding mechanisms, operating philosophies, and best maintenance practices is essential to achieving good product quality, energy savings, and high throughput.

Several pieces of information are needed to select and size a mill. You must know the required annual capacity, whether batch or continuous operation will be required, which upstream and downstream processes will be needed for the mill, and the properties (such as size and shape) of the finished product. Fully characterizing the feed material is essential to identifying the right mill for the job.

This article gives a detailed description of hammer mill and jet mill operation, and describes how to characterize the feed material and control product particle size.

Understand the size-reduction application

Before designing a milling system, or making any purchases, you must fully understand the requirements of your size-reduction application. Ask yourself:

- Why do I need to perform size reduction?
- Can I buy the right-sized material cheaply and directly from any suppliers?
- Can the superfine particle be made more inexpensively from a bottom-up method, such as synthesis?

If the answers to these questions indicate a size reduction step in your process is essential, you should verify the other process requirements, such as production capacity, product particle size, and particle-size distribution.

The capacity requirement of the milled product in your process must be illustrated clearly in a yearly, monthly, daily, and hourly rate. The capacity not only determines the mill equipment size, but also dictates how to operate the mill, whether continuous or batch operation is required, and whether the process can be performed in-house or if a tolling service is a better option.

The required product size is an important grinding cost factor, especially for fine-size grinding. You should evaluate particles in several size ranges to determine the effect of size on product quality. In general, the grinding cost increases significantly as the product particle size decreases. The coarsest size conducive to good product quality should be used whenever possible.

Sometimes, particle shape, bulk density, or flowability are also important to the quality of the final ground product. Bulk density and flowability are strongly associated with particle shape. In general, smooth, round particles yield high bulk density and good flowability. The particle shape is determined by the properties of the feed material and the size-reduction mechanism of the mill. However, because the feed material typically cannot be modified, particle shape is strongly influenced by the type of grinding mill selected.

Characterize the feed material

To determine the type of mill you will need for your application, gather information about the nature of the material to be ground. Certain properties are important, such as hardness, toughness, stickiness, melting point and thermal instability, explosibility, toxicity, particle size and particle-size distribution, flowability, and bulk density.

Hardness/softness. The Mohs scale of mineral hardness is frequently used to specify hardness. A hammer mill is typically good for grinding softer materials with Mohs hardness ranging from 1 to 5, while a jet mill can grind materials with Mohs hardness as high as 10. High hardness materials become very abrasive; therefore, they are not suitable for high-speed hammer mills. In a typical jet mill, grinding action is caused mainly by particle-particle collisions, so wear to the mill's internals is less of an issue.

Toughness/brittleness. Toughness is a material's ability to absorb energy and plastically deform without fracturing. A feed stream containing a material with a high toughness (such as rubber) may need to be cooled — which reduces molecular mobility and increases brittleness — before grinding the material. Liquid nitrogen is often used to cool the feed stream in hammer mills for grinding tough materials. However, liquid nitrogen is seldom used in jet milling operations due to the swift heat exchange between the material and the grinding gas. The grinding gas heats up the supercooled feed stream, and the material loses its brittleness when it absorbs this heat.

Stickiness. This property is sometimes related to moisture content. However, stickiness can also increase with higher fineness. Material with high stickiness creates problems in all aspects of the grinding process, including feeding (*e.g.,* making metering into the mill difficult), grinding (*e.g.,* plugging the hammer mill screen or blocking the air classifier of a jet mill), and collection (*e.g.,* plugging the bag filters).

There are two ways to grind sticky materials. The first solution is to dry the material prior to grinding, or dry and grind it at the same time by sweeping hot air through the mill. As an alternative, water can be added to the material and it can be ground wet; this solution is suitable for hammer mill operation but not for jet mills.

Melting point and thermal instability. Jet mills can grind materials with low melting points effectively because these mills have intrinsic cooling due to compressed air expansion in the body of the mill. With the help of sweeping air, hammer mills may also be able to process materials with low melting points for coarse grinding applications.

Explosibility. The risk of dust explosions must be taken into account when a material is ground very fine in a milling process. Dust-laden air can give rise to devastating dust explosions. Unless the material is one of the few commonly known to present no dust explosion risk (a stable oxide, for example, such as titanium dioxide or sand), you should always test the material's explosibility characteristics.

The material's dust deflagration index (K_{st}) and maximum explosion pressure (P_{max}) values should be used to design any necessary dust explosion protection devices, such as active suppression systems, explosion vents, and isolation systems. The minimum ignition energy (MIE) can provide guidance for selecting a safe unloading method for materials received in bags, bulk bags, or drums. Materials with a low MIE (*e.g.,* <10 mJ) require special equipment and operational precautions for handling, packing, and unpacking the material. Targeted use of blanketing with an inert gas, such as nitrogen, is another strategy to help prevent combustible dust explosions. Electrical grounding and bonding on related equipment and pipes are also important to eliminate static charges, which are a source of ignition.

Dust explosion risks may be even more serious in plant rooms containing the milling machinery than in the machinery housing itself. The hazard arises from bad housekeeping, which allows dust to accumulate on ledges, ceiling beams, and other surfaces. After an initial dust explosion in or around milling equipment, a second explosion can occur from the dust that has been allowed to accumulate in the plant room. Although the first explosion may be minor, it disturbs the dust on surfaces throughout the room, which fills the room with a dust cloud. The dust cloud is then ignited by an ignition source, typically a small fire generated by the first explosion. The secondary explosion is usually far more devastating than the first explosion, because a much greater volume of dust is involved. Good housekeeping is the best way to prevent secondary dust explosions.

Toxicity. Understanding your material's toxicity is critical to protecting both workers and the environment. For a highly toxic material, a totally enclosed milling system is recommended. Enclosed systems are available for both hammer mill and jet mill operations. A product collection bag filter and a fan system are typically part of the milling system, and the negative pressure inside the milling system prevents any material from leaking out. To prevent a toxic material release into the environment during a dust explosion event, you may need to use a chemical suppression system to contain a dust explosion inside the dust collection system, rather than a less-expensive explosion panel that vents pressure and flames outside the building.

Particle size and particle-size distribution. Knowing the feed material's average particle size and maximum particle size will assist you in selecting the right feed device to ensure a uniform feeding rate to the mill. This information will also help you determine whether a multiple-stage milling system is necessary. When measuring the particle size of the feed material, it is very important to obtain a representative sample. This is not a trivial task since the feed is typically stored in large packages. For example, the ratio of the mass of material contained in a large bulk bag to the mass of a sample of that material being measured in a laboratory particle-size analyzer is on the order of 10^9:1.

Flowability. The flowability of a material is related to the physical properties of the material, such as moisture content and surface chemistry. In dry milling applications, a high-moisture feed material can flow poorly and build up on the grinding chamber wall, classifier wheel, and conveying line. This can reduce mill capacity and air classifier performance. Particle surface chemistry can affect many material properties that affect flow, including stickiness, affinity for water, and tendency to accumulate electrostatic charge.

The flowability of the feed material dictates which type of surge bin and feeder you should select to effectively feed material into the mill. For instance, live-bottom screw feeders are typically used for feeding materials with poor flowability.

Bulk density. The size of both the feed surge bin and the feeder is based on the bulk density of the feed material. For materials with very low bulk densities, the feed chute to the mill should be carefully designed to prevent plugging. The bulk density can also be used to estimate the weight of the material bed in the grinding chamber during jet milling.

Perform milling tests

Once you fully understand the requirements for your application and the material properties, have your vendor conduct milling tests with your material. These tests will validate the feasibility of the milling operation and help you determine what size mill you will need. Milling tests are important even if the supplier has data from a similar application, since every material has unique properties.

The first test is a screening test (*i.e.,* feasibility test) that determines which type of mill will work for your application. Using the feed material from your application, the vendor will provide a sample of the milled material for product evaluation. It is useful, but not essential, to witness tests at this stage. Sometimes, two or three vendors may be selected for the screening test.

Vendors that successfully pass the initial screening tests should be asked to make confirmatory tests (*i.e.,* pilot tests) to define the product quality, equipment capacity, equipment reliability, and cost. These tests should be witnessed and should be carried out using production equipment where possible, under conditions that will provide a spectrum of particle sizes. The range of particle sizes can be used to determine the effect of particle size on product quality.

The particles created during this test series should be prepared and processed into finished goods, if possible. Exercise care to assure that representative samples are evaluated. If more than one equipment type can make a satisfactory product, use the process economics to make the final decision on equipment. You will also need to select auxiliary equipment required for a complete plant installation, which may include dust filters, cyclones, blowers, air compressors and compressed air delivery piping, a tramp metal eliminator, etc.

A supervised confirmatory test run should be conducted with the selected equipment type to provide the following data:

- power requirement, number of electric motors, and horsepower rating
- product temperature rise
- air requirements, such as flowrate and static pressure
- capacity of equipment and effect of feed rate on performance
- effect of grinding rotor peripheral speed on grinding performance.

Other observations on equipment operation will be helpful, for example, noting corrosion or wear rate, plugging problems, necessary controls, ease of change of operating conditions, hazards from tramp metal or other foreign material, ease of equipment cleanout, and dust and housekeeping problems.

Several vendors may offer the same type of equipment. The final selection should be made based on the economics of the whole process, including space constraints and costs of all equipment and installation, as well as power, manpower, and maintenance requirements.

Hammer mill operation

The hammer mill (Figure 1) is the most popular mechanical impact mill and is often used for general-purpose grinding. It is comprised of a rotating shaft fitted with freely swinging hammers mounted in a cage. Inside the cage is a breaker plate, against which the feed is disintegrated, chiefly by the impact from the hammers. Hammer mills create a wide range of product sizes, from millimeters to several-tens of microns.

A high shaft speed is needed to increase the chance of a hammer making contact with a particle; hence, hammer mills have relatively high specific grinding energy. The mill's maximum peripheral speed (*i.e.,* tip speed) is typically between 18,000–24,000 ft/min for fine grinding applications.

Gravity feed and discharge is typically used for crushing applications, and air transport is used for fine grinding applications. The high-speed rotating hammers within the cage draw air through the mill. Therefore, when using gravity discharge, a vent port in the outlet of the mill or the product collection container is necessary to release the sucked-in air.

Hammer mills are sensitive to damage from metals or large stones. Installing a magnetic separator and a heavy-matter drop box upstream of the machine is common.

The ultimate goal of material grinding is to obtain the desired particle size. In any given size-reduction application, the specific properties of the material being processed play a key role in how the desired product particle size is achieved. Other factors that control the particle size and size distribution in a hammer mill include screen size and rotor speed, as well as hammer size, number, and length.

Screen size. When material enters the grinding chamber of a hammer mill, it must be reduced to a size small enough to pass through screen openings before it can exit the mill. Screen size is determined by the application and grinding requirements. Smaller particle sizes are achieved using smaller screen perforations. Of course, capacity is sacrificed by grinding finer (or smaller) particles. In the majority of hammer mill applications, screen size provides up to 70% control over the product particle size. A small hammer mill may only have one screen, while large hammer mills may have two screens (*i.e.,* a set of screens).

Rotor speed. In general, the faster the rotor speed, the greater the number of impacts between the hammers and the material, producing particles of a finer size. Every material has a corresponding minimum rotor speed within a defined machine; only above that speed can the mill grind the material efficiently. At a speed below the minimum value, the applied stresses on the particles from the hammers are largely below a threshold value that is needed to extend cracks inside the particles and break them into small pieces. At low speeds, the hammers will only increase the heat content of the particles.

Hammer size, number, and length. In most cases, particle strength increases as the size of the particles decreases, and the mean stress in a smaller particle has to be higher to propagate a crack. Therefore, higher stress caused by the greater force from a heavy hammer will produce a finer product.

Hammers may be placed in the mill in differing quantities. More hammers will provide a finer grind at a reduced capacity. Fewer hammers can provide increased capacity but a coarser grind.

Hammer length can be changed to provide increased or decreased hammer-to-screen clearance. Longer hammers provide reduced hammer-to-screen clearance, which creates a finer grind at a reduced capacity. Shorter hammers provide increased hammer-to-screen clearance, which gives a coarser grind at a larger capacity.

Although the screen size, rotor speed, and hammer characteristics affect the finished particle size, other key factors affect the throughput or performance of hammer mills. These include the mill feeder type, discharge systems, and maintenance practices.

How to feed hammer mills? Hammer mills are typically fed by a vibratory feeder, screw feeder, or a rotary valve. No matter what type of feeder is used, it is important that the hammer mill is fed as evenly across the inlet width as possible. This will allow for even wear of components and reduced opportunities for vibration. It is also important that the hammer mill is fed an even stream of material. This will provide a steady load on the motor, increasing efficiency and throughput.

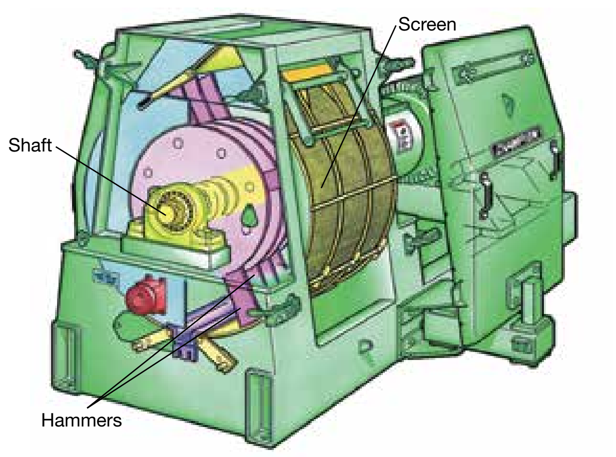
Regardless of the type of feeder installed, it should be equipped with a variable speed drive to control the feeder motor speed. For maximum grinding output, the hammer mill motor should be run as close to full load amperage as possible. From the hammer mill motor nameplate, note the full load amps or watts of the main motor, then mark the ammeter or wattmeter to indicate the point at which this full load will be reached. To adjust the load on the main motor, increase or decrease the feed rate.

How to assist product discharge? Air-assisted discharge is an effective way for hammer mills to grind light, fibrous, and low-density material to a fine particle size. The airflow induced by a fan sucks the light feed material into the grinding chamber, and pulls the particles from the grinding chamber through the screen openings, transporting the ground material to a product collector.

A poorly designed air system can reduce the capacity by up to 50% of the production design. The key to success is to determine an optimized air flowrate for typical operation. Two rules of thumb are widely used in the industry:

• use 1–3 ft^3/min air volume per square inch of hammer-mill screen area

• use 800–1,200 cfm air volume per ton per hour production rate.



▲ **Figure 1.** In a hammer mill, mechanical impact from swinging hammers disintegrates the feed. A screen or grate allows particles of a small enough size to pass through. Image courtesy of CPM Roskamp Champion (Waterloo, IA).

Article continues on next page

These rules must be used very carefully since every hammer mill application is unique. It is always recommended to run pilot tests at a vendor's site to determine the necessary air flowrate.

How to perform maintenance? The operation and maintenance of a hammer mill should be assigned only to qualified personnel. Systematic and planned maintenance will assure continuous service and low grinding costs. Follow lubrication instructions carefully and regularly, and ensure that the motors, bearings, and couplings are properly lubricated. Plant maintenance personnel should set up a routine and systematic lubrication schedule.

Both screens and hammers must be maintained properly for maximum production. In general, one set of hammers should wear out 2–4 sets of screens. The screens should be replaced when edges dull; do not wait for screens to blow out. The new screens should be of equal thickness and have the same opening area as the originals, and the same hole stagger. Screens may be turned and re-rolled to use all edges.

When one corner of the hammer wears, the mill's direction of rotation may be reversed to wear the other corner, achieving longer hammer life. A two-hole hammer (*i.e.,* hammers installed on both ends of a rod) provides four wear edges, as the hammers can be reversed too. Be aware that, due to wear patterns within the hammer mill, the outer hammers on each hinge pin are typically thicker than the central hammers.

Jet mill operation

Jet mills are suitable for superfine grinding down to five microns or smaller. The grinding action in a jet mill is created by the high-velocity collisions between particles driven by multiple jets of air or steam. A compressor and nozzles are needed to transform pressure into kinetic energy, so that the feed may attain a sufficient momentum to effect breakage by impact. The energy requirement of a jet mill is high; therefore, jet mills are generally employed only for specialty products that need superfine grinding, for which the economics are viable.

Jet mills can be categorized into two main designs based on how they control the final product particle size:

• fluidized-bed jet mills (FBJMs), which have built-in air classifiers

• jet mills without built-in air classifiers, which have internal classification action in the grinding chamber.

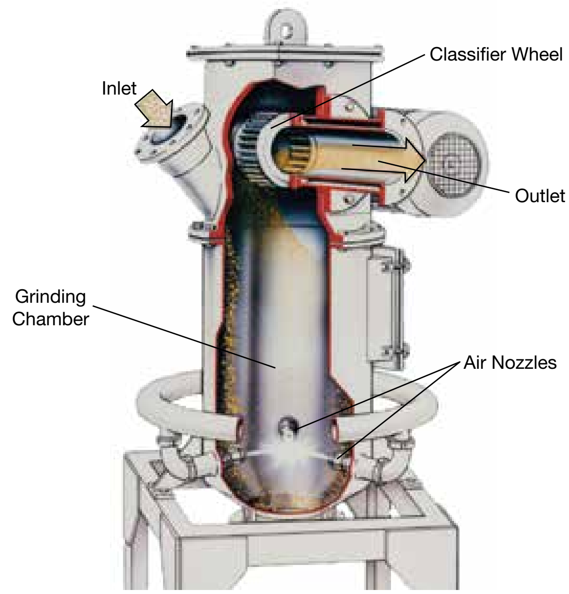
The grinding gas is generally air or superheated steam. Air is supplied at 50–120 psig and steam is supplied at 100–220 psig and 392–980°F. Depending on site availability, steam is typically cheaper than air. However, steam can only be used for feeds that are not heat sensitive.

In general, FBJMs are more expensive than jet mills without air classifiers. The FBJM (Figure 2) is widely used across various industries for dry materials, and creates particle sizes down to 1–10 μm. The mill's air classifier tightly controls the final product's maximum particle size. This gives the FBJM a unique advantage over other jet mills.

To ensure that you select the right size and model FBJM, you must have a thorough understanding of your application requirements and material characteristics, and you should conduct pilot-scale milling tests with a representative sample.

FBJM systems (Figure 3) can be divided into three sections: the feeding section, milling section, and air-handling section. The system's feeding section includes a material charge hopper, a feeder (*e.g.,* a screw feeder), and an air-isolation valve (*e.g.,* a double-flap valve). The milling section (Figure 2) includes a material inlet, a grinding chamber, air nozzles, an air classifier, and an air-and-material outlet. The machine is typically mounted on load cells, which monitor the weight of the material in the grinding chamber and communicate with the control system to regulate the feeding speed. The air-handling section includes an air compressor, multiple conveying lines, a dust collector, a fan, and other ancillary equipment. If superheated steam is used, then a boiler, instead of an air compressor, will be needed.

Air classifiers separate particles by the combined effect of centrifugal force and drag forces from air friction (Figure 4). These forces determine the direction in which a given size particle will move and whether it is classified as "fines" or "coarses." In an air classifier, these forces are influenced by the diameter and speed of rotation of the rotating wheel, its dimension and number of blades fitted to it, and the volume and velocity of air passing through it.



▲ **Figure 2.** A fluidized-bed jet mill (FBJM) creates finer particles than a hammer mill. The air classifier tightly controls the outlet particle size. Image courtesy of Hosokawa Micron Powder Systems (Summit, NJ).

The two key operating parameters that are typically adjustable to get the desired particle size and mill capacity are the air classifier speed and grinding gas pressure.

Air classifier speed. When optimizing your FBJM system, the air classifier speed is typically one of the first adjustments. As material enters the spinning classifier wheel, the exhaust airstream carries the smaller, lighter particles to the mill's discharge, while the wheel's centrifugal force rejects the larger, heavier particles back into the grinding chamber. The balance between these two forces can be described by:

$$\frac{1}{2}C_D\rho_g V_r^2\frac{\pi}{4}x^2=\frac{\pi}{6}x^3\rho_s a_c \qquad (1)$$

where C_D is the drag coefficient, ρ_g is the air density, V_r is the air radial velocity, x is the classification particle-size cut (*i.e.,* the size at which particles have a 50% chance of being rejected and a 50% chance of being product), ρ_s is the particle density, and a_c is the centrifugal acceleration.

After some simplification of Eq. 1, the particle-size cut, x, can be described by Eq. 2:

$$x \propto \frac{\mu_g^{0.375}\rho_g^{0.25}Q_g^{0.875}}{\rho_s^{0.625}N^{1.25}} \qquad (2)$$

where μ_g is the air's dynamic viscosity, Q_g is the gas flowrate, and N is the classifier's rotation speed in rpm.

Since the air viscosity, air density, and particle density are usually constant in a size reduction application, the main adjustable parameters are gas flowrate and classifier speed in Eq. 2. If mill nozzle size and nozzle supplied gas pressure are fixed, the gas flowrate is constant too. Now, only air classifier speed can be adjusted to control the final product particle size. Equation 2 shows that increasing classifier speed will generate finer product particle size. However, increasing the classifier speed will also reduce the mill throughput.

Grinding gas pressure. The other important parameter to control product particle size and mill throughput is the grinding gas pressure. For superfine jet milling, a convergent-divergent nozzle, called a de Laval nozzle, is typically used (Figure 5). When analyzing the gas flow in a de Laval nozzle, assume that the gas flow is isentropic (*i.e.,* at constant entropy). The grinding gas flowrate through the nozzle can be calculated:

$$Q_g = P_1 k A_t\sqrt{\frac{1}{kRT_1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \qquad (3)$$

where P_1 is the absolute gas pressure at the nozzle inlet, k is the gas isentropic expansion factor (for air, k =1.4), A_t is the cross-sectional area at the throat, R is the universal gas constant, and T_1 is the absolute temperature at the nozzle inlet.

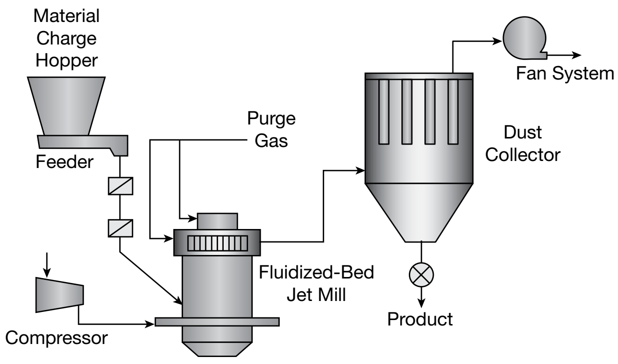
As the grinding gas pressure increases, the grinding gas flowrate increases proportionally. At the same time, the nozzle exit velocity also increases:

$$V_2=\sqrt{\frac{RT_1}{M}\frac{2k}{k-1}\left(1-\left[\frac{P_2}{P_1}\right]^{\frac{k-1}{k}}\right)} \qquad (4)$$

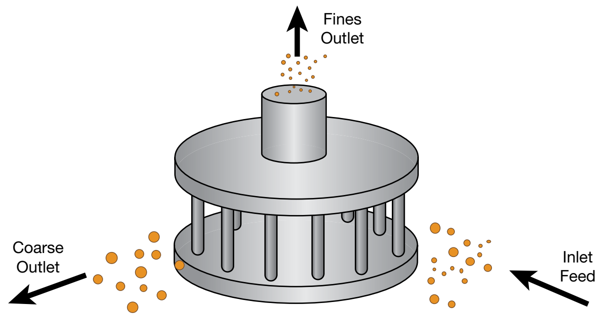
where V_2 is the nozzle exit velocity, M is the molecular weight of the gas, and P_2 is the absolute pressure at nozzle exit (*i.e.,* the pressure of the grinding chamber).

A higher nozzle exit velocity grinds the particle finer due to the higher kinetic impact energy. Higher grinding gas flowrate improves the mill throughput, but results in a larger particle-size cut (according to Eq. 2). Therefore, to keep the same particle-size cut, it is necessary to increase the classifier rotation speed.

If the designed mill throughput is not achieved, you may increase the grinding gas pressure. However, there is an upper limit on the gas pressure. Other ways to improve mill throughput include modifying the nozzle size and grinding gas temperature.



▲ **Figure 3.** A typical FBJM system will have a material charge hopper and a feeder that supplies the milling section with the feed stream. A dust collector system is used to move the product out of the mill.



▲ **Figure 4.** In an air classifier, particles are separated by size. As material enters the spinning classifier wheel, the exhaust airstream carries the smaller, lighter particles, called fines, to the mill's discharge. The wheel's centrifugal force rejects the larger, heavier particles back into the grinding chamber.

Article continues on next page

Nozzle size. Using a larger nozzle size will increase the gas flowrate. For example, if the mill is designed for 8-mm nozzles, it is possible to use 9-mm or even 10-mm nozzles for the same machine. From Eq. 3, we know the gas flowrate is proportional to the square of the nozzle diameter (d):

$$Q_g \propto d^2 \tag{5}$$

Therefore, as long as the compressor has enough capacity, changing to a 9-mm nozzle from an 8-mm nozzle may increase the mill throughput by over 25%.

Grinding gas temperature. In a de Laval nozzle, the kinetic energy at the nozzle exit comes at the expense of the grinding gas' potential energy (pressure) and internal energy (temperature). Both pressure and temperature are reduced significantly. The gas temperature (T_2) at the nozzle exit can be expressed as:

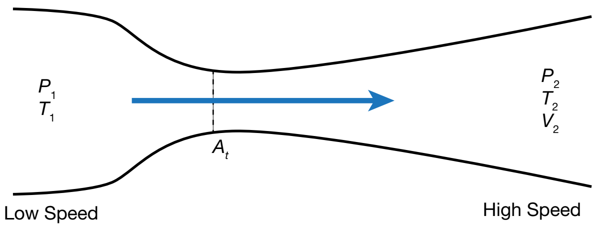
$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \tag{6}$$

If the compressed grinding air enters at 20°C and 6 barg, the air temperature at the nozzle exit is about –105°C! Though this cooling effect is beneficial for milling a heat sensitive material, the cooling effect may also condense moisture brought in by the feed material. The condensed water may cause fouling of the fine ground particles on the surface of the classifier wheels. Fouling increases the load on the classifier motor, reduces mill throughput, changes product size distribution, or can trip the classifier motor.

The gas temperature (T_2) at the nozzle exit can be increased by properly heating the compressed air, which will prevent the water vapor condensing issue. Increasing T_1 will have two additional effects: it will decrease the grinding gas flowrate (as per Eq. 3) and it will increase the nozzle exit velocity (Eq. 4). In general, the velocity through the nozzle increases about 60 ft/min for every degree Fahrenheit increase in air temperature. In common applications, heating the operating gas can improve the mill throughput by 15%.

After a milling job is complete, it is generally sufficient to use a dry cloth, hand brush, and/or industrial vacuum cleaner to clean the jet mill inside and out. Never use high-pressure cleaners or compressed air for cleaning, since it may cause serious damage to the bearings in the classifier motor.

The parts subject to the most wear in the FBJM are the air classifier and the nozzles. Periodically check the wear on the classifier. If irregular wear patterns cause the classifying wheel to run out of balance, then it must be changed. Otherwise, the service life of the related anti-friction bearings will be shortened due to the high degree of stress placed on them by the unbalanced classifier wheel.



▲ **Figure 5.** A de Laval nozzle is pinched in the middle and it is used to accelerate gas passing through it to a supersonic speed, by converting both the potential and heat energy of the flow into kinetic energy.

Closing thoughts

When considering the total cost of a size reduction system, it is necessary to consider the milling system as a whole, including conveyors, screening or separation devices, dust filters and collectors, etc. The total cost of a milling process can be divided into three parts, each of which accounts for about one-third of the total:

- capital cost of the milling equipment
- energy cost of running all the devices in the milling system
- maintenance and operating labor costs.

Size reduction is a complex process, and it is not surprising that in spite of intensive efforts to analyze the physics and mechanics of grinding processes, we are still a long way from being able to design, operate, control, and predict results on the basis of fundamental scientific principles. Thoroughly understanding your application, fully characterizing your feed material, and conducting milling tests are essential to the success of selecting, installing, and operating the best available commercial equipment at your plant. CEP

GARY LIU, P.E., PhD, is an engineering consultant at DuPont with 14 years of experience in solids handling and processing (Email: gary.liu@dupont.com; Phone: (302) 695-7627). He specializes in particle surface modification, size reduction, pneumatic and mechanical conveying, powder characterization and flow, solids mixing and blending, dust collection, process scale-up and optimization, and troubleshooting commercial manufacturing processes. He has authored more than 35 journal papers and conference proceedings, as well as four patents. He is a senior member of AIChE and an active member of the Particle Technology Forum. He has a BS in engineering mechanics from Xian Jiaotong Univ., China, and a PhD in mechanical engineering from New Jersey Institute of Technology. He is a licensed Professional Engineer in Delaware.

Literature Cited

1. **Perry, R. H., and D. W. Green,** "Perry's Chemical Engineers' Handbook," 7th Ed., Section 21, McGraw-Hill, New York, NY (1997).
2. **Lynch, A. J.,** "Comminution Handbook," Australasian Institute of Mining and Metallurgy, Carlton, Australia (2015).
3. **Fayed, M. E., and L. Otten,** "Handbook of Powder Science and Technology," 2nd ed., Ch. 12, Van Nostrand Reinhold Co., New York, NY (1997).
4. **Lowrison, G. C.,** "Crushing and Grinding," Butterworths, London, U.K. (1974).