Paper No. : **04**
Paper Title : **Unit Operations in Food processing**
Module – 30 : **Size reduction – 1: Grinding**

30.1 Introduction

Size reduction is the term related to the process in which the size of solids are reduced or broken into smaller items. It involves creation of smaller mass units from bigger mass units of the same material. To change this, the bigger mass units need to be subjected by the application of an external energy. Reduction of size is brought about by means of mechanical aids without change in chemical properties of the materials. In the various industries solids materials are reduced by different methods for different purposes. For examples crude ore are broken to desirable size, synthetic chemicals are converted into power, sheets of plastic are cut into various pieces, etc. Reducing the particle size is also permits separation of unwanted materials by mechanical methods.

The extent of the breakdown of a solid particle may be expressed by the *reduction ratio*, which is the average size of the feed materials divided by the average size of the products. In this context, the term average size depends on the method of measurement. In the industry, screening or sieving is widely used to evaluate particle size distribution in granular materials and powders. In case of coarse crushing the size reduction ratios is below 8:1 and in fine grinding it is more than 100:1.

Solids are broken mainly by four different ways, which are used in size-reduction machines. They are (1) compression, (2) impact, (3) attrition, or rubbing, and (4) cutting. Examples are a nutcracker, a sledge hammer, a file, and a pair of shears. In these four types of processes, compression is used for coarse reduction of hard solids which give relatively few fines; impact yields coarse, medium, or fine products; attrition gives very fine products from soft, nonabrasive materials. Cutting gives a definite particle size or a definite shape, with very less or no fines.

The aim of the size reduction operations is to produce particles within a specified size range. To classify the particles into different size range screening is the technique most widely used for the purpose. To achieve a desired reduction ratio, it may be necessary to carry out the size reduction operation in a number of stages. In other wards a different type of size reduction equipment may be used in each stage and different size of screens may be employed between stages. An example of a multistage operation is shown in Fig. 30.1.

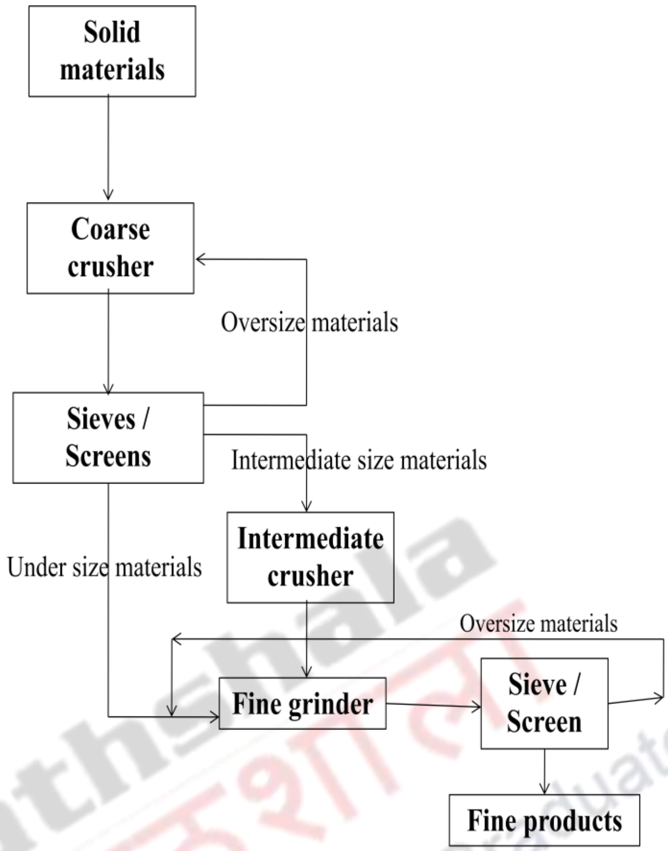

FIGURE 30.1 A typical size reduction flow sheet

30.2 Principles of comminution

Comminution is a generic term for size reduction; crushers and grinders are types of comminuting equipment used for size reduction of agricultural products. An ideal crusher or grinder would (1) have a high capacity, (2) require a less power input per unit of product, (3) yield a product of same size or the desired size, and (4) easy and trouble free operation. The usual method of studying the performance of equipment is to set up an ideal operation as a standard one and then, compare the characteristics of the actual equipment with those of the ideal unit, and analysis the results for the difference between the two.

Unlike an ideal crusher or grinder, an actual equipment does not gives a uniform product, whether the feed is uniformly sized or not. The products always contain a mixture of particles, ranging from a definite maximum dimension to a submicroscopic minimum size. In some types of grinders fine particles are minimized, but they are not eliminated. If the feed is homogeneous, both in the shapes, chemical and physical structure, the shapes of the individual units in the product may be quite uniform; otherwise, the grains in the various sizes of a single product may vary considerably in proportions.

30.3 Energy and power requirements in comminution

In the process of crushing and grinding operation, the major expenditure is the requirements power, so the factors that control this cost are important. In size reduction process, the particles of feed material are first distorted and strained. The energy necessary to strain them is stored temporarily in the solid as mechanical energy of stress, just as mechanical energy can be stored in a coiled spring. When an additional energy is applied to the stresses particles, they are unshaped beyond their ultimate strength and suddenly rupture into fragments. Hence new surface is generated. Since a unit area of solid has a definite amount of surface energy, the creation of new surface requires work, which is supplied by the release of energy of stress when the particle breaks.

To estimate the energy requirement for a specified reduction in particle size, various mathematical models are available. These are based on the assumption that the energy "dE" required to produce a small change "d*x*" in the size of a unit mass of material can be expressed as a power function of the size of the material. Thus:

$$\frac{dE}{dx} = -\frac{K}{x^n} \qquad \text{……………………. 30.1}$$

Rittinger's Law is based on the assumption that the energy required should be proportional to the new surface area produced, i.e. n=2. So:

$$\frac{dE}{dx} = -\frac{K}{x^2} \qquad \text{……………………… 30.2}$$

by integrating equation 30.2

$$E = K\left[\frac{1}{x_2} - \frac{1}{x_1}\right] \qquad \text{……………………….. 30.3}$$

Where x_1 is the average initial size of the feed particles, x_2 is the average size of the product particles, E is the energy requirement per unit mass and K is a constant, known as Rittinger's constant. Rittinger's law has been found to hold better for fine grinding.

Kick's Law is based on the assumption that the energy required should be proportional to the size reduction ratio, i.e. n = 1. So:

$$\frac{dE}{dx} = -\frac{K}{x} \qquad \text{……………………… 30.4}$$

by integrating equation 30.4

$$E = K \ln \frac{x_1}{x_2} \qquad \text{.......................... 30.5}$$

Kick's law has been found to apply best to coarse crushing.

In ***Bond's Law***, *n* is given the value 3/2. So:

$$\frac{dE}{dx} = -\frac{K}{x^{3/2}} \qquad \text{......................... 30.6}$$

by integrating equation 30.6

$$E = 2K\left[\frac{1}{\sqrt{x_2}} - \frac{1}{\sqrt{x_1}}\right] \qquad \text{.......................... 30.7}$$

Or *Bond's law* can be expressed as

$$\frac{P}{F} = 0.3162\, w_i \left[\frac{1}{\sqrt{D_p}} - \frac{1}{\sqrt{D_f}}\right] \qquad \text{............................ 30.8}$$

Where P is the power in KW, F is the feed rate in t/hr, D_f is 80% of feed passes through mesh of diameter D_f, D_p is 80% of products passes through mesh of diameter D_p, and w_i is the constant called work index.

Bond's law has been found to apply well to a variety of materials undergoing coarse, intermediate and fine grinding.

30.4 Size reduction equipment

The various types of size reduction equipment are crushers, grinders, ultrafine grinders, and cutting machines. The size reduction of large pieces of solid materials into small lumps is done by crusher which is commonly used for heavy work. A primary crusher may break large pieces of solid materials into 6 to 10 inch lumps. A secondary crusher reduces these lumps to a particles size of nearly 1/4 inch. *Grinders* reduce crushed feed to powder. The product from an intermediate grinder might pass a 40-mesh screen; most of the product from a fine grinder would pass a 200-mesh screen. An *ultrafine grinder* is mainly used for feed particles of size ¼ inch and the product size is typically 1 to 50 µm. *Cutters* give particles of definite size and shape to nearly 2 to 10 mm in length.

The various types of size reduction machines are:

A Crushers (coarse and fine)

1. Jaw crushers
2. Gyratory crushers
3. Crushing rolls

B Grinding (intermediate and fine)

1. Hammer mills; impactors
2. Rolling-compression mills
    a. Bowl mills
    b. Roller mills
3. Attrition mills
4. Revolving mills
    a. Rod mills
    b. Ball mills; pebble mills
    c. Tube mills; compartment mills

C Ultrafine grinders

1. Hammer mills with internal classification
2. Fluid-energy mills
3. Agitated mills

D Cutting machines

1. Knife cutter; dicers; slitters

These machines do their work in distinctly different ways. Crushers works on the principle of slow compression action whereas grinders employ impact and attrition, sometimes combined with compression. In case of ultrafine grinders, it operate mainly by attrition. A cutting action is of course characteristic of cutters, dicers, and slitters.

30.4.1 Crusher

For large quanties of solids, the low speed machine like crushers are used for coarse reduction. The common types are jaw crushers, gyratory crushers, smooth-roll crushers, and toothed-roll crushers. The first three machine are operate by compression and can break large lumps of very hard materials, as in the primary and secondary reduction of rocks and ores. Toothed-roll crushers break the feed apart as well as crushing it; they handle softer feeds like coal, bone, and soft shale.

30.4.1.1 Jaw crushers*:* In a jaw crusher feed is admitted between two jaws. These tow jaws are set to form a ‘V’ shape opening at the top. One jaw is fixed, or anvil, which is nearly vertical and does not move and the other is swinging jaw, reciprocates in a horizontal plane (Fig. 30.2). The swinging jaw makes an angle of 20° to 30° with the fixed jaw and driven by an eccentric unit, thereby produce compressive force to lumps caught between the jaws. After required reduction they drop out the bottom of the machine. The jaws open and close 250 to 400 times per minute.

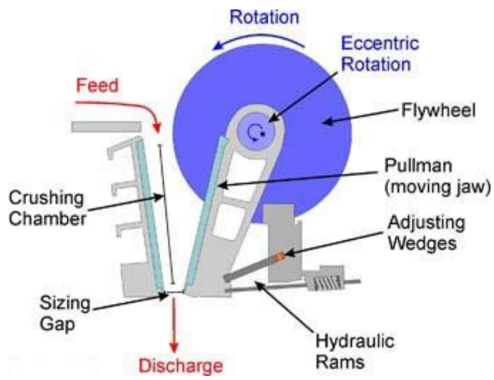

FIGURE 30.2 Jaw crusher (Courtesy: McGraw-Hill publ.)

30.4.1.2 Gyratory crusher: In a gyratory crusher, jaws between in which the feed is admitted is circular jaws. The material is being crushed at some point at all times in gyratory crusher. It consists of a funnel-shaped casing, open at the top and a conical crushing head gyrates inside the casing, as shown in Fig. 30.3. An eccentric unit drives the bottom end of the shaft which gyrates the crushing head. Therefore, the bottom of the crushing head moves toward, and then away from, the stationary wall. Solids are caught in the V-shaped space between the head and the casing and are repeatedly broken until they pass from the discharge. The crushing head is free to rotate on the shaft and turns slowly because of friction with the material being crushed.

The speed of the crushing head is in range of 125 to 425 gyrations per minute. The discharge from a gyratory crusher is continuous instead of intermittent as in a jaw crusher. The load on the motor is nearly uniform. Less maintenance and low power per ton of material crushed is required, as compared to other crushers. The capacity of a gyratory crusher depend capacity of a gyratory crusher depends on the jaw setting, the impact strength of the feed, and the speed of gyration of the machine. The capacity is almost independent of the compressive strength of the material being crushed.

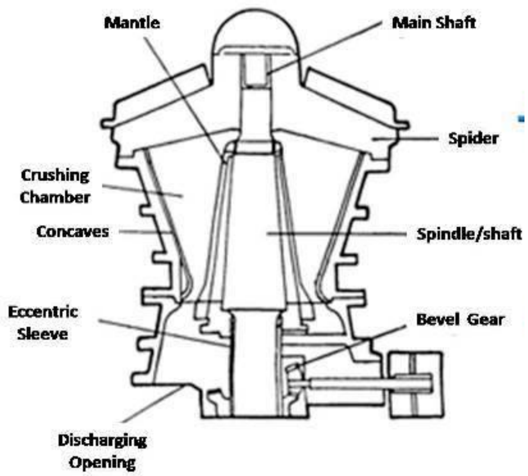

FIGURE 30.3 Gyratory crusher (Courtesy: McGraw-Hill publ.)

30.4.1.3 Crushing rolls

Smooth-roll crushers: Two heavy smooth-faced metal rolls rotating on parallel horizontal axes are the working elements of the smooth-roll crusher illustrated in Fig. 30.4. The rolls rotate toward each other at the same speed. Feed materials are caught between the rolls and broken in compression and then drop out below. The rolls have relatively narrow faces and are large in diameter so that they can "nip" moderately large lumps. Typical rolls are 600 mm in diameter with a 300 mm face to 2000 mm in diameter with a 914 mm face. Speed of the roll range from 50 to 300 rpm. Smooth-roll crushers are secondary crushers, with feeds 12 to 75 mm in size and products 12 to 1 mm.

The limiting size $D_{p,max}$ of particles that can be caught by the rolls depends on the coefficient of friction between the material and the roll surface, but in most cases it can be estimated from the following relation:

$$D_{p,max} = 0.04R + d$$

where $D_{p,max}$ = Maximum size of material

R = roll radius

d = half the width of the gap between the rolls

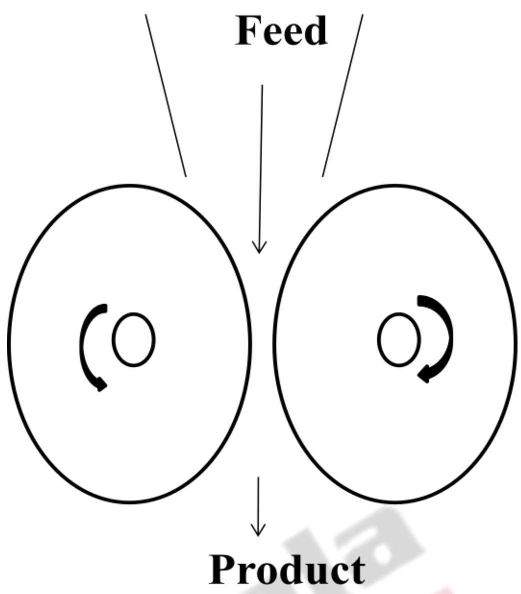

FIGURE 30.4 Smooth-roll crusher

Tooth-roll crushers: In such roll crushers the roll faces are corrugations, breaker bars, or teeth structures. Tooth-roll crushers may contain two rolls, as in smooth-roll crushers, or only one roll working against a stationary curved breaker plate. A single-roll toothed crusher is shown in Fig. 30.5. These type of crushers known as disintegrators, consists two corrugated rolls rotating at different speeds, which broken the feed apart. Otherwise a small high-speed roll with transverse breaker bars on its face rotating toward a large slow-speed smooth roll. Some crushing rolls for coarse feeds material carry heavy pyramidal teeth. Other designs use many number of thin-toothed disks that saw through slabs or sheets of material. Toothed-roll crushers are much more versatile than smooth-roll crushers, only the limitation that they cannot handle very hard solids. The principles of operation are compression, impact, and shear, not by compression alone, as in case of smooth-roll machines. Some heavy-duty toothed double-roll crushers are used for the primary size-reduction of coal and similar materials. The particle size of the feed materials may be more than 500mm and their capacity up to 500 tons/h.

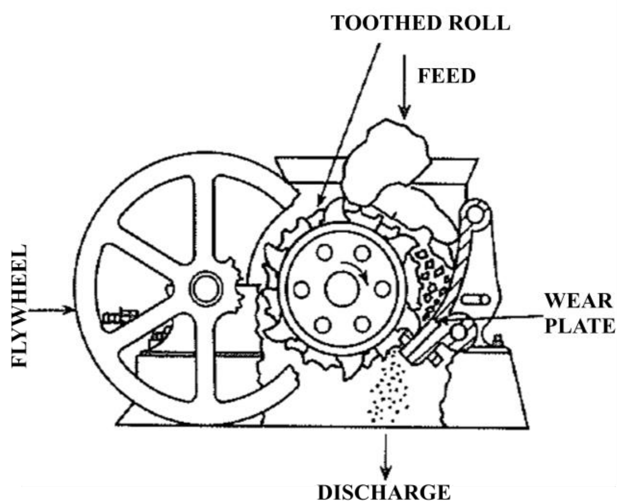

FIGURE 30.5 Single –roll toothed crusher (Courtesy: McGraw-Hill publ.)

30.4.2 Grinders

The term grinder describes a variety of size-reduction machines for intermediate duty. The product obtained from a crusher is often fed to a grinder to reduced the particle to powder. The common types of grinders are hammer mills and impactors, rolling-compression machines, attrition mills, and tumbling mills.

30.4.2.1 Hammer mills and impactors**:** These mills consists a high-speed rotor rotating inside a cylindrical casing. The shaft is usually kept horizontal. Feed is admitted to the mill from the top of the casing. Materials are broken and fall out through a screen at bottom. The materials are broken by sets of swinging hammers attached to a rotor disk. A particle of feed entering into grinding zone cannot escape being struck by the hammers. It make into pieces, which fly against a stationary anvil plate inside the casing and break into still smaller fragments. These in turn are rubbed into powder by the hammers and pushed through a screen that covers the discharge opening.

An *impacto*r, which does not contain any grate or screen is resembles to a heavy-duty hammer mill. In such particles are broken by impact alone. Impactors are often primary-reduction machines for rock and ore, processing up to 600 ton/h. They give particles that are more nearly equi-dimensional (more “cubical”) than the slab-shaped particles from a jaw crusher or gyratory crusher. The impactor rotor may be run in either direction to prolong the efficiency of the hammers.

30.4.2.2 Rolling-compression machines**:** In such mill the feed material are caught and crushed between a roller member and the face of a grinding ring or casing. The most common types are rolling-ring pulverizers, bowl mills, and roller mills. In the *roller mill*, cylindrical rollers are vertical which press outward with a huge force against a stationary anvil ring or bull ring. They are driven at medium speeds in a circular motion. Plows takes the feed materials from the floor of the mill and put them between the ring and the rolls, where the size-reduction takes place. Product is taken out of the mill by a stream of air to a classifier separator, from which oversize materials are returned to the mill for further reduction. In a *bowl mill* and some roller mills the bowl or ring is driven; the rollers rotate on stationary axes, which may he vertical or horizontal. These kinds of mills are used for the reduction of limestone, cement clinker, and coal. They pulverize up to 50 ton/h. When classifying separator / screen are used, the product may be as fine as 99 percent through a 200-mesh screen.

30.4.2.3 Attrition mills**:** In *attrition mill* materials of soft solids are rubbed between the grooved flat faces of rotating circular disks. These mills are also known as burr or plate mills. The axis of the disks is may be horizontal or vertical. In a single-runner mill one disk plate is stationary while other rotates and in a double-runner machine both disks are rotate at high speed in opposite directions. Feed materials are admitted through an opening in the hub of one of the disks and it passes outward through the narrow gap between the disks and discharges from the periphery into a stationary casing. The width of the gap is adjustable, within limits. One grinding plate is mounted with spring so that the disks can separate if unbreakable material gets into the mill. A single-runner attrition mill is shown in Fig. 30.6. Single-runner mills consist disks of buhrstone or emery rock for breaking solids like clay and talc, or disk of metal for solids like wood, starch, insecticide powders, and carnauba wax. Metal disks are usually made up of white iron. For corrosive materials, stainless steel disks are used. Double—runner mills are used to process softer feeds and grind to finer products than single-runner mills. Air is often drawn through the mill to remove the product and prevent choking. The heat generated on the disk by the reduction operation may be cooled with water or refrigerated brine.

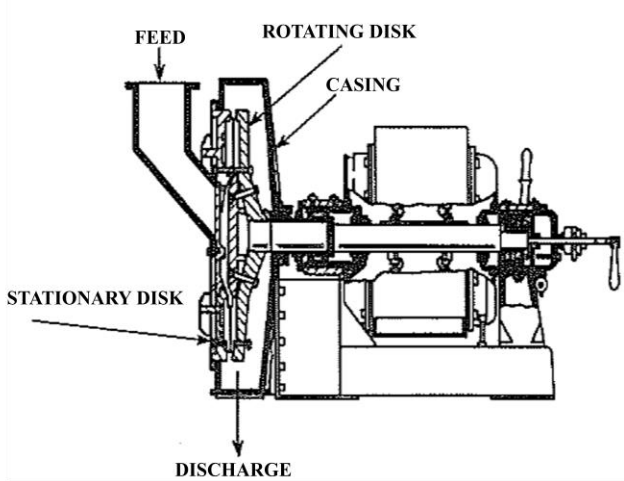

FIGURE 30.6 Attrition mill (Courtesy: McGraw-Hill publ.)

The diameter of disks in a single-runner mill is 250 to 1400 mm, rotating at 350 to 700 rpm. Disks in double-runner mills rotate at about 1200 to 7000 rpm. The feed must enter at a uniform controlled rate and should be pre-crushed to a maximum particle size of about 12 mm. Attrition mills grind from 1/2 to 8 ton/h to products that will pass a 200-mesh screen. The power requirement is depends on the property of the feed and the degree of size-reduction accomplished and is much higher as comparable to other mills and crushers. In general, power requirement is between 8 and 80 kWh per ton of product.

30.4.2.4 Revolving mills**:** Revolving mill is also known as *tumbling mill*. It contains a cylindrical shell, which rotate lowly about a horizontal axis and filled to about half its volume with a solid grinding medium. The shell is usually made up of steel, lined with high-carbon steel plate, porcelain, silica rock, or rubber. The grinding medium is metal rods in a rod mill, lengths of chain or balls of metal, rubber, or wood in a ball mill, flint pebbles or porcelain or zircon spheres in a pebble mill.

In tumbling mills feed may be admitted in continuous or batch. In a batch tumbling mill a measured quantity of the feed to be ground is provided into the mill through an opening in the shell. Then the opening is closed and the mill rotated few hours; it is then stopped and the product is discharged. In a continuous mill the feed rate is uniform and continuous through the revolving shell which entering at one end through a hollow trunnion and leaving at the other end through the trunnion or through peripheral openings in the shell.

In all tumbling mills, the grinding elements are carried up the side of the shell nearly to the top, from where they fall on the particles underneath. The energy required in lifting the grinding units is utilized in reducing the size of the particles. In some tumbling mills, as in case of *rod mill*, the size-reduction is done by rolling compression and by attrition. The rods slide downward and roll over one another. The grinding rods are usually steel and of diameter 25 to 125 mm, with several sizes present at all times in any given mill. The rods extend the full length of the mill. They are sometimes kept from twisting out of line by conical ends on the shell. Rod mills are intermediate grinders, which may reduce up to nearly 20 mm feed to nearly 10 mesh, often preparing the product from a crusher for final reduction in a ball mill. They yield a product with little oversize and a minimum of fines.

In a *ball mill or pebble mill* the size-reduction is carried out by impact as the balls or pebbles drop from near the top of the shell. In a large ball mill the diameter of shell may be 3 m and 4.25m in length. The balls are 15 to 125 mm in diameter; the pebbles in a pebble mill are 50 to 175 mm in size. A *tube mill* is a continuous mill contain a long cylindrical shell, excellent for grinding to very fine powders in a single pass. The tube mill is converted into a *compartment mill* by putting slotted transverse partitions. Various compartment may contain large balls, small ball, and pebbles. This segregation of the grinding media into elements of different size and weight aids considerably in avoiding wasted work, for the large, heavy balls break only the large particles, without interference by the fines. The small, light balls fall only on small particles, not on large lumps which cannot break.

Segregation of the grinding units in one chamber is a characteristic of the *conical ball mill*. Feed enters from one side through a 60° cone into the primary grinding zone, where the shell diameter is maximum. Product discharge through the 30^{o} cone from another side. In such mill the balls are of different size and become smaller due to wear as the mill is operated. So new large balls are added periodically. As the shell of such a mill turns, the large balls move toward the point of maximum diameter, and the small balls migrate toward the discharge. The initial breaking of the feed particles, therefore, is done by the largest balls dropping the greatest distance; small particles are ground by small balls dropping a much smaller distance.

When the mill is rotated, the balls are picked up by the mill wall and carried nearly to the top, where they break contact with the wall and fall to the bottom to be picked up again. Centrifugal force keeps the balls in contact with the wall and with each other during the upward movement. While in contact with the wall, the balls do some grinding by slipping and rolling over each other, but most of the grinding occurs at the zone of impact, where the free-falling balls strike the bottom of the mill. The faster the mill is rotated, the farther the balls are carried up inside the mill and the greater the power consumption. The added power is profitably used because the higher the balls are when they are released, the greater the impact at the bottom and the larger the productive capacity of the mill. If the speed is too high, however, the balls are carried over and the mill is said to be centrifuging. The speed at which centrifuging occurs is called the *critical speed*. Little or no grinding is done when a mill is centrifuging, and operating speeds must be less than the critical. The critical speed can be calculated from the expression:

$$n_c = \frac{1}{2\pi}\sqrt{\frac{g}{R - r}}$$

Where, n_c is the critical speed in rev/sec, g is acceleration due to gravity, 9.8 m/s^2, R is radius of the mill, m and r is radius of the ball, m.

Tumbling mills run at 65 to 80 percent of the critical speed, with the lower values for wet grinding in viscous suspensions.

30.4.3 Ultrafine Grinders

Most of the commercial powders contain particles size ranging 1 to 20 μm, with substantially all particles passing a standard screen of 325-mesh that has 44 μm wide opening. The mills that used to reduce to such size particles are called *ultrafine grinders*. Ultrafine grinding of dry powder is done by grinders, such as high-speed hammer mills, provided with internal or external classification, and by fluid-energy or jet mills. Ultrafine wet grinding is done in agitated mills.

30.4.3.1 Classifying hammer mills**:** A hammer mill with internal classification is the Mikro-Atomizer illustrated in Fig. 30.7. A set of swing hammers is held between two rotor disks, much as in a conventional hammer mill. In addition to the hammers the rotor shaft carries two fans, which draw air through the mill in the direction shown in the figure and discharge into ducts leading to collectors for the product. On the rotor disks are short radial vanes for separating oversize particles from those of acceptable size. In the grinding zone the particles of solid are given a high rotational velocity. Due to centrifugal force, coarse particles are concentrated along the wall of the chamber. The airstream carries finer particles inward from the grinding zone toward the shaft in the direction AB. The separator vanes tend to throw particles outward in the direction BA. Whether or not a given particle passes between the separator vanes and out to the discharge depends on which force predominates—the drag exerted by the air or the centrifugal force exerted by the vanes. Acceptably fine particles are carried through; particles that are too large are thrown back for farther reduction in the grinding chamber. The maximum particle size of the product is varied by changing the rotor speed or the size and number of the separator vanes. Mills of this kind reduce 1 or 2 ton/h to an average particle size of 1 to 20 μm, with an energy requirement of about 40 kWh/metric ton.

***30.4.3.2 Fluid energy mills*:** In such mills the particles are suspended in a high-velocity gas stream which flows in a circular or elliptical path. In some design there are jets that oppose one another or vigorously agitate a fluidized bed. When the particles strike or rub against the walls of the confining chamber, size-reduction occurs. Also most of the reduction is carried out by inter-particle attrition. Due to internal classification, the larger particles are reduced to the desired size.

The suspending gas which may be compressed air or superheated steam, admitted through nozzles at a pressure of 7 atm. In the mill the grinding chamber is an oval loop of pipe 25 to 200 mm in diameter and 1.2 to 2.4 m high. Feed enters through a venturi injector which is situated near the bottom of the loop. At the upper end of the loop classification of the ground particles takes place. As the gas stream flows around upper bend at high speed, the coarser particles are thrown outward against the outer wall while the fines congregate at the inner wall. A discharge opening in the inner wall at this point leads to a cyclone separator and a bag collector for the product. Fluid-energy mills can accept feed particles as large as 12 mm but are more effective when the feed particles are no larger than 100-mesh. They reduce up to 1 ton/h of nonstick solid to particles averaging 1/2 to 10 μm in diameter, using 1 to 4 kg of steam or 6 to 9 kg of air per kilogram of product. Loop mills can process up to 6000 kg/h.

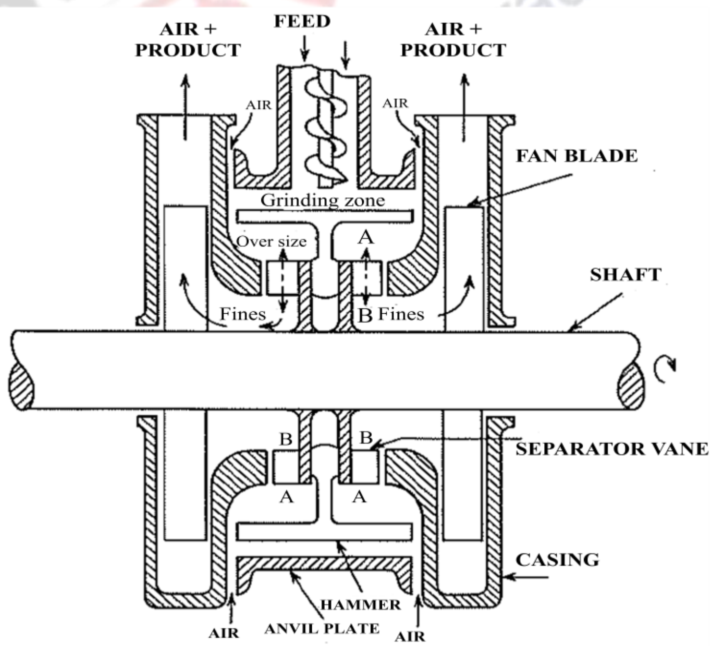

FIGURE 30.7 Principle of Mikro-Atomizer (Courtesy: McGraw-Hill publ.)

***30.4.3.3 Agitated mills*:** In such mills, the grinding medium consists of hard solid elements such as balls, pellets, or sand grains. The grinding medium is suspended in a vertical vessel of 4 to 1200 L in capacity which is filled with liquid. In some designs the charge is agitated with a multi-armed impeller; in others, used especially for grinding hard materials (such as silica or titanium dioxide), a reciprocating central column "vibrates" the vessel contents at about 20 Hz. A concentrated feed slurry is admitted at the top, and product (with some liquid) is discharged through a screen at the bottom. Agitated mills are especially useful in producing particles 1 μm in size or finer.

30.4.4 Cutting Machines

In the size-reduction operation if the feed stocks are too tenacious or too resilient, they cannot be broken by compression, impact, or attrition, Hence cutting machines are used. In some cases of size-reduction the feed must be reduced to particles of fixed dimensions. These requirements are met by devices that cut, chop, or tear the feed into a product with the desired characteristics. Cutting machines like rotary knife cutters and granulators used for the application of a variety of processes but are especially well adapted to size-reduction problems in the manufacture of rubber and plastics. In agricultural industry, cutting machines are mainly used to cut fruits and vegetables.

***30.4.4.1 Knife cutter*:** A rotary knife cutter contains a horizontal rotor rotating at 200 to 900 rpm in a cylindrical chamber. The rotor consist of 2 to 12 flying knives with edges of tempered steel or stellite passing with close clearance over 1 to 7 stationary bed knives. Feed particles enter the chamber from top are cut several hundred times per minute and withdrawn at the bottom through a screen with 5 to 8 mm openings. Sometimes the flying knives are parallel with the bed knives; sometimes, depending on the properties of the feed, they cut at an angle. Rotary cutters and granulators are similar in design. A granulator yields more or less irregular pieces; a cutter may yield cubes, thin squares, or diamonds.

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