# UNIT 5 SIZE REDUCTION

**Structure**



## 5.0 OBJECTIVES

By the time you have studied this unit, you should be able to:

- understand the principles and methods of size reduction;
- describe various size reduction equipments and their efficiencies; and
- understand the importance of size reduction and able to decide the suitability of different machinery for various uses.

## 5.1 INTRODUCTION

The term *size reduction* is applied to all the ways in which particles of solids are cut or broken into smaller pieces. Throughout the process industries solids are reduced in size and shape by different methods for different purposes. Reduction in size is brought about by mechanical means without any change in chemical properties of the materials. During size reduction operation, chunks of large particles are crushed or reduced to workable size. In this process uniformity in size and shape of the individual particles of the resultant product is desirable, but difficult to attain. Size reduction sometimes leads to increased reactivity of solids, helps separation of unwanted ingredients and reduces the bulk of fibrous materials for easier handling.

## 5.2 PRINCIPLES OF SIZE REDUCTION

Crushers and grinders are the equipment mostly used for size reduction of agricultural products. An ideal size reducer should fulfil the following conditions, namely (1) large capacity, (2) should yield a pre-desired sized product or range of size, (3) small power input requirement per unit of product handled and (4) easy and trouble free operation. Usually the performance of any milling equipment is compared with respect to an ideal operation as standard. The characteristics of the actual equipment are compared with those of the ideal unit.

Size reduction results in the production of small particles which may be required either for larger surface area or because of their definite shape, size and number. Amount of power required to create smaller particles is one of the parameters of the efficiency of operation. Second parameter is the desired uniformity of size. The actual unit seldom yields a uniform sized product. Irrespective of uniformity of feed size the ground product consists of a mixture of various particle sizes. In some equipment there is a provision to control the magnitude of the largest particles like the hammer mill, but the fine size is beyond control. In some size reducing machine fines are minimized but they can not be eliminated altogether.

## 5.3 METHODS OF SIZE REDUCTION

Solids may be broken in many different ways, but only four of them are commonly used in size-reduction machines: (1) compression, (2) impact, (3) attrition or rubbing, and (4) cutting. A nutcracker, a hammer, a file, and a pair of scissors exemplify these four types of action. Sometimes size reduction results from the attrition of a particle by one or more other particles or from intense shear in the supporting fluid. In general, compression is used for coarse reduction of hard solids, to give relatively few fines; impact gives coarse, medium, or fine products; attrition yields very fine products from soft, nonabrasive materials. Cutting gives a definite particle size and sometimes a definite shape, with few or no fines.

**Crushing:** When an external force is applied on a material in excess of its strength, the material fails because of its rupture in many directions. The particles produced after crushing are irregular in shape and size. The type of material and method of force application affects the characteristics of new surfaces and particles. Food grain flour, grits and meal, ground feed for livestock are made by crushing process. Crushing is also used to extract oil from oilseeds and juice from sugarcane.

**Impact:** When a material is subjected to sudden blow of force in excess of its strength, it fails, like cracking of nut with the help of a hammer. Operation of hammer mill is an example of dynamic force application by impact method.

**Shearing:** It is a process of size reduction which combines cutting and crushing. The shearing units consist of a knife and a bar. If the edge of knife or shearing edge is thin enough and sharp, the size reduction process nears to that of cutting, whereas a thick and dull shearing edge performs like a crusher. In a good shearing unit the knife is usually thick enough to overcome the shock resulting from material hitting. In an ideal shearing unit the clearance between the bar and the knife should be as small as practicable and the knife as sharp and thin as possible.

**Cutting:** In this method, size reduction is accomplished by forcing a sharp and thin knife through the material. In the process minimum deformation and rupture of the material results and the new surface created is more or less undamaged. An ideal cutting device is a knife of excellent sharpness and it should be as thin as practicable. The size of vegetables and fruits are reduced by cutting.

## 5.4 SIZE REDUCTION EQUIPMENT

Size-reduction equipment is divided into crushers, grinders, ultrafine grinders, and cutting machines. *Crushers* do the heavy work of breaking large pieces of solid material into small lumps. A primary crusher operates on run-of-mine material, accepting anything that comes from the mine face and breaking it into 150 to 250 mm lumps. A secondary crusher reduces these lumps to particles perhaps 6 mm in size. *Grinders* reduce crushed feed to powder. The product from an intermediate grinder might pass a 4O mesh screen; most of the product from a fine grinder would pass a 200 mesh screen with a *74 $\mu m$* opening. An *ultrafine grinder* accepts feed particles no larger than 6 mm; the product size is typically 1 to 50 $\mu m$. *Cutters* give particles of definite size and shape, 2 to 10 mm in length.

The principal types of size-reduction machines are as follows:

A. Crushers (coarse and fine)

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

B. Grinders (intermediate and fine)

   1. Hammer mills; impactors
   2. Rolling-compression mills

      a) Bowl mills
      b) Roller mills

   3. Attrition mills
   4. Tumbling 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
   4. Colloidal mills

D. Cutting machines

   1. Knife cutters; dicers; slitters

These machines do their work in distinctly different ways. Compression is the characteristic action of crushers. Grinders employ impact and attrition, sometimes combined with compression; ultrafine grinders operate principally by attrition. A cutting action is of course characteristic of cutters, dicers, and slitters.

### 5.4.1 Crushers

Crushers are slow-speed machines for coarse reduction of large quantities of solids. The main types are jaw crushers, gyratory crushers, smooth-roll crushers, and toothed-roll crushers. The first three operate by compression and can break large lumps of very hard materials, as in the primary and secondary reduction. Toothed-roll crushers tear the feed apart as well as crushing it; they handle softer feeds like coal, bone, and soft shale.

**Jaw crushers:** In a jaw crusher feed is admitted between two jaws, set to form a V open at the top. One jaw, the fixed, or anvil, jaw, is nearly vertical and does not move; the other, the swinging jaw, reciprocates in a horizontal plane. It makes an angle of 20° to 30° with the anvil jaw. An eccentric drives it so that it applies great compressive force to lumps caught between the jaws. The jaw faces are flat or slightly bulged; they may carry shallow horizontal grooves. Large lumps caught between the upper parts of the jaws are broken, drop into the narrower space below, and are recrushed the next time the jaws close. After sufficient reduction they drop out the bottom of the machine. The jaws open and close 250 to 400 times per minute.

The most common type of jaw crusher is illustrated in Figure 5.1. In this machine an eccentric drives a pitman connected to two toggle plates, one of which is pinned to the frame and the other to the swinging jaw. The pivot point is at the top of the movable jaw or above the top of the jaws on the centerline of the jaw opening. The greatest amount of motion is at the bottom of the V, which means that there is little tendency for a crusher of this kind to choke. Some machines with a 1.8 by 2 m feed opening can accept rocks 1.8 m in diameter and crush 1200 ton/h to a maximum product size of 250 mm. Smaller secondary crushers reduce the particle size of precrushed feed to 6 to 50 mm at much lower rates of throughput.

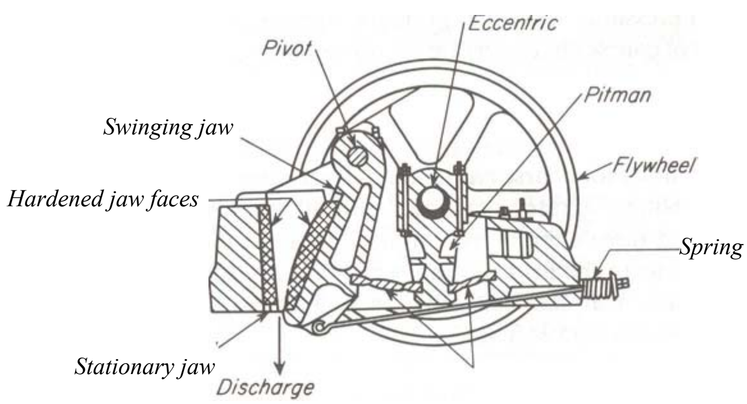


**Figure 5.1: Jaw crusher**

**Gyratory crushers:** A gyratory crusher may be looked upon as a jaw crusher with circular jaws, between which material is being crushed at some point at all times. A conical crushing head gyrates inside a funnel-shaped casing, open at the top. As shown in Figure 5.2, the crushing head is carried on a heavy shaft pivoted at the top of the machine. An eccentric drives the bottom end of the shaft. At any point on the periphery of the casing, therefore, the bottom of the crushing head moves toward, and then away from, the stationary wall. Solids caught in the V-shaped space between the head and the casing are broken and rebroken until they pass out the bottom. 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 typically 125 to 425 gyrations per minute. Because some part of the crushing head is working at all times, the discharge from a gyratory is continuous instead of intermittent as in a jaw crusher. The load on the motor is nearly uniform; less maintenance is required than with a jaw crusher; and the power requirement per ton of material crushed is smaller. The biggest gyratories handle up to 4500 ton/h. The capacity of a gyratory crusher varies with 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.

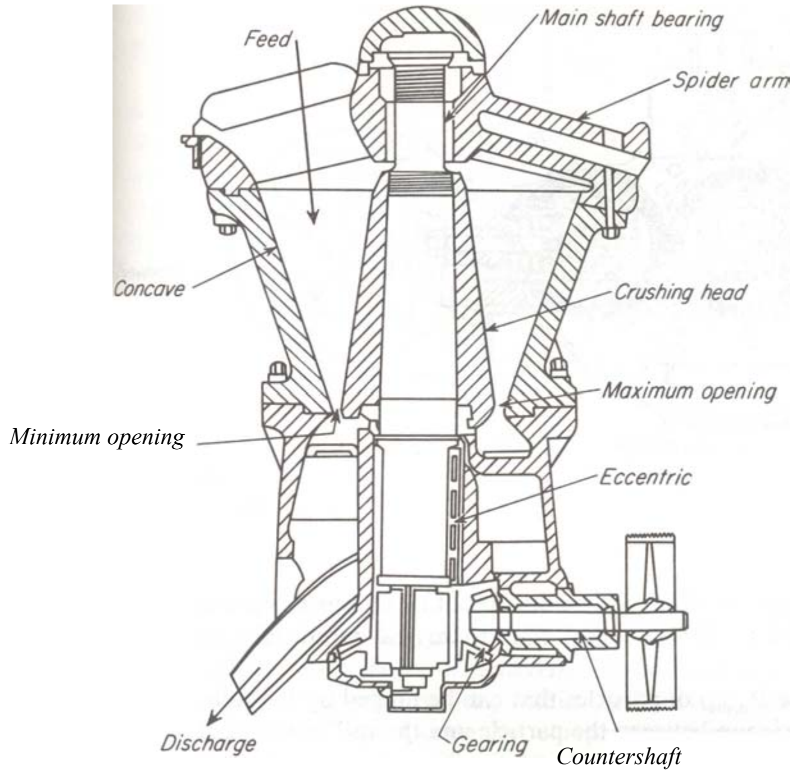


**Figure 5.2: Gyratory crusher**

**Smooth-roll crushers:** Two heavy smooth-faced metal rolls turning on parallel horizontal axes are the working elements of the smooth-roll crusher illustrated in Figure 5.3. Particles of feed caught between the rolls are broken in compression and drop out below. The rolls turn toward each other at the same speed. They 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 3OO mm face to 2000 mm in diameter with a 914 mm face. Roll speeds range from 50 to 300 r/min.

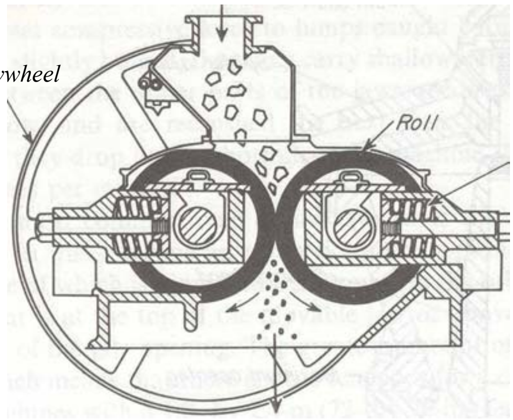


**Figure 5.3: Smooth roll crusher**

Smooth-roll crushers are secondary crushers, with feeds 12 to 75 mm in size and products 12 mm to about 1 mm. The limiting size $D_{p.max.}$ of particles that can be nipped by the rolls depends on the coefficient of friction between the particle and the roll surface, but in most cases it can be estimated from the simple relation.

$$D_{p.max.} = 0.04R + d5.1 \qquad (5.1)$$

where R = roll radius

d = half the width of the gap between the rolls.

The maximum size of the product is approximately equal to *2d.*

The particle size of the product depends on the spacing between the rolls, as does the capacity of a given machine. Smooth-roll crushers give few fines and virtually no oversize. They operate most effectively when set to give a reduction ratio of 3 or 4 to 1; that is, the maximum particle diameter of the product is one-third or one-fourth that of the feed. The forces exerted by the roll are very great, from 8700 to 70,000 N/cm of roll width. To allow unbreakable material to pass through without damaging the machine, at least one roll must be spring mounted.

**Toothed-roll crushers:** In many roll crushers the roll faces carry corrugations, breaker bars, or teeth. Such 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 Figure 5.4 Machines known as *disintegrators* contain two corrugated rolls turning at different speeds, which tear the feed apart, or a small high-speed roll with transverse breaker bars on its face turning toward a large slow-speed smooth roll. Some crushing rolls for coarse feeds carry heavy pyramidal teeth.

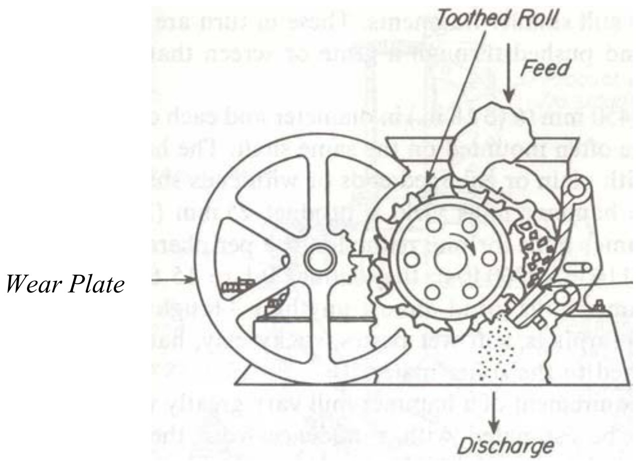


**Figure 5.4: Single-roll tooth crusher**

Other designs utilize a large number of thin-toothed disks that saw through slabs or sheets of material Toothed-roll crushers are much more versatile than smooth-roll crushers, within the limitation that they cannot handle very hard solids. They operate by compression, impact, and shear, not by compression alone, as do smooth-roll machines. They are not limited by the problem of nip inherent with smooth rolls and can therefore reduce much larger particles. Some heavy-duty toothed double-roll crushers are used for the primary reduction of coal and similar materials. The particle size of the feed to these machines may be as great as 500 mm; their capacity ranges up to 500 tons/h.

### 5.4.2 Grinders

The term *grinder* describes a variety of size-reduction machines for intermediate duty. The product from a crusher is often fed to a grinder, in which it is reduced to powder. The chief types of commercial grinders described in this section are hammer mills and impactors, rolling-compression machines, attrition mills, and tumbling mills.

**Hammer mills and impactors:** These mills all contain a high-speed rotor turning inside a cylindrical casing. The shaft is usually horizontal Feed dropped into the top of the casing is broken and falls out through a bottom opening. In a hammer mill the particles are broken by sets of swing hammers pinned to a rotor disk. A particle of feed entering the grinding zone cannot escape being struck by the hammers. It shatters 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 grate or screen that covers the discharge opening.

Several rotor disks, 150 to 450 mm in diameter and each carrying four to eight swing hammers, are often mounted on the same shaft. The hammers may be straight bars of metal with plain or enlarged ends or with ends sharpened to a cutting edge. Intermediate hammer mills yield a product 25 mm to 20-mesh in particle size. In hammer mills for fine reduction the peripheral speed of the hammer tips may reach 110 m/s; they reduce 0.1 to 15 ton/h to sizes finer than 200-mesh. Hammer mills grind almost anything tough fibrous solids like bark or leather, steel turnings, soft wet pastes, sticky clay, hard rock. For fine reduction they are limited to the softer materials.

The capacity and power requirement of a hammer mill vary greatly with the nature of the feed and cannot be estimated with confidence from theoretical considerations. They are best found from published information or better from small-scale or full-scale tests of the mill with a sample of the actual material to be ground. Commercial mills typically reduce 60 to 240 kg of solid per kilowatt hour of energy consumed.

An *impactor,* illustrated in Figure 5.5, resembles a heavy-duty hammer mill except that it contains no grate or screen. Particles are broken by impact alone, without the rubbing action characteristic of a hammer mill. Impactors are often primary-reduction machines, processing up to 600 ton/h. They give particles that are more nearly equidimensional (more "cubical") than the slab-shaped particles from a jaw crusher or gyratory crusher. The rotor in an impactor, as in many hammer mills, may be run in either direction to prolong the life of the hammers.

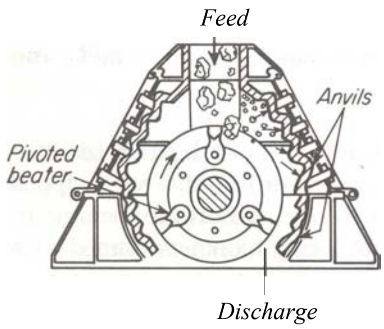


**Figure 5.5: Impactor**

**Rolling-compression machines:** In this kind of mill the solid particles are caught and crushed between a rolling member and the face of a ring or casing. The most common types are rolling-ring pulverizers, bowl mills, and roller mills. In the roller mill illustrated in Figure 5.6, vertical cylindrical rollers press outward with great force against a stationary anvil ring or bullring. They are driven at moderate speeds in a circular path. Plows lift the solid lumps from the floor of the mill and direct them between the ring and the rolls, where the reduction takes place. Product is swept out of the mill by a stream of air to a classifier separator, from which oversize particles 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 be vertical or horizontal. They pulverize up to 50 ton/h. When classification is used, the product may be as fine as 99 percent through a 200-mesh screen.

**Attrition mills:** In an attrition mill particles of soft solids are rubbed between the grooved flat faces of rotating circular disks. The axis of the disks is usually horizontal, sometimes vertical. In a single-runner mill one disk is stationary and one rotates; in a double-runner machine both disks are driven at high speed in opposite directions. Feed enters through an opening in the hub of one of the disks; it passes outward through the narrow gap between, the disks and discharges from the periphery into a stationary casing. The width of the gap, within limits, is adjustable. At least one grinding plate is spring mounted so that the disks can separate if unbreakable material gets into the mill. Mills with different patterns of grooves, corrugations, or teeth on the disks perform a variety of operations, including grinding, cracking, granulating, and shredding, and even some operations not related to size reduction at all, such as blending.

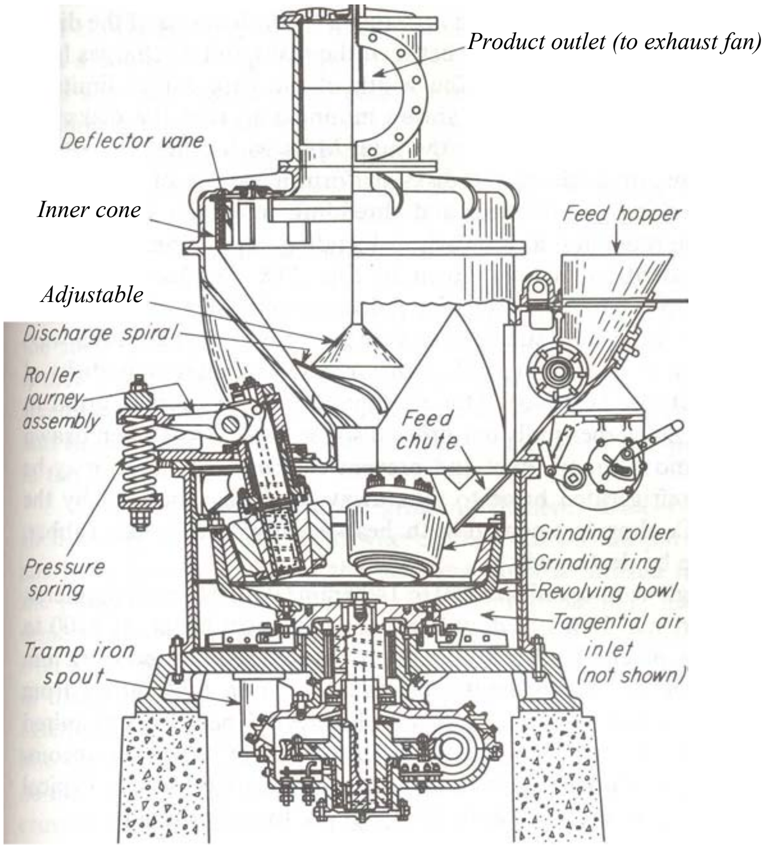


**Figure 5.6: Roller mill**

A single-runner attrition mill is shown in Figure 5.7. Single-runner mills contain disks of buhrstone or rock emery for reducing solids like spices, starch, insecticide powders, and carnauba wax. Metal disks are usually of white iron, although for corrosive materials disks of stainless steel are sometimes necessary. Double-runner mills, in general, grind to finer products than single-runner mills but process softer feeds. Air is often drawn through the mill to remove the product and prevent choking. The disks may be cooled with water or refrigerated brine to take away the heat generated by the reduction operation. Cooling is essential with heat-sensitive solids like spices, rubber which would otherwise be destroyed.

The disks of a single-runner mill are 250 to 1400 mm in diameter; turning at 350 to 700 r/min. Disks in double-runner mills turn faster, at 1200 to 7000 r/min. The feed is precrushed to a maximum particle size of about 12 mm and must enter at a uniform controlled rate. Attrition mills grind from 1 to 8 ton/h to products that will pass a 200-mesh screen. The energy required depends strongly on the nature of the feed and the degree of reduction accomplished and is much higher than in the mills and crushers described so far. Typical values are between 8 and 80 kWh (10 and 100 hp-h) per ton of product.

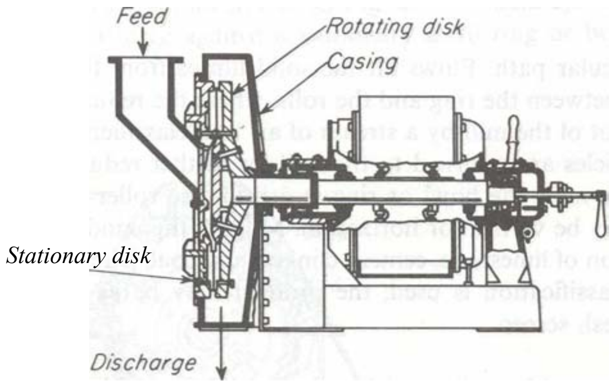


**Figure 5.7: Attrition mill**

**Tumbling mills**: A typical tumbling mill is shown in Figure 5.8. A cylindrical shell slowly turning about a horizontal axis and filled to about half its volume with a solid grinding medium forms a tumbling mill. The shell is usually 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. For intermediate and fine reduction of abrasive materials tumbling mills are unequaled.

Unlike the mills previously discussed, all of which require continuous feed, tumbling mills may be continuous or batch. In a batch machine a measured quantity of the solid to be ground is loaded into the mill through an opening in the shell. The opening is then closed and the mill turned on for several hours; it is then stopped and the product is discharged. In a continuous mill the solid flows steadily through the revolving shell, 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 whence they fall on the particles underneath. The energy expended in lifting the grinding units is utilized in reducing the size of the particles. In some tumbling mills, as in a *rod mill,* much of the reduction is done by rolling compression and by attrition as the rods slide downward and roll over one another. The grinding rods are usually steel, 25 to 125 mm in diameter, 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, reducing a 20 mm feed to perhaps l0 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.

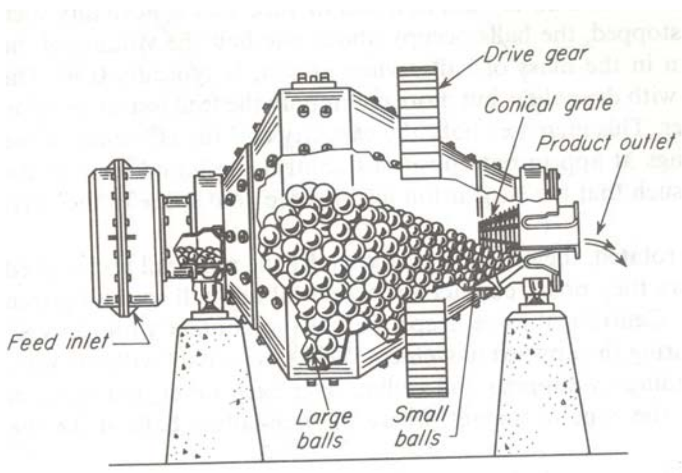


**Figure 5.8: Conical ball mill**

In a *ball mill* or *pebble mill* most of the reduction is done by impact as the balls or pebbles drop from near the top of the shell. In a large ball mill the shell might be 3 m in diameter and 4.25 m long. The balls are 25 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 with a long cylindrical shell, in which material is ground for 2 to 5 times as long as in the shorter ball mill. Tube mills are excellent for grinding to very fine powders in a single pass where the amount of energy consumed is not of primary importance. Putting slotted transverse partitions in a tube mill converts it into a *compartment mill.* One compartment may contain large balls, another small balls, and a third 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 they cannot break.

Segregation of the grinding units in a single chamber is a characteristic of the *conical ball mill* illustrated in Figure 5.8. Feed enters from the left through a 60° cone into the primary grinding zone, where the diameter of the shell is a maximum. Product leaves through the 30° cone to the right. A mill of this kind contains balls of different sizes, all of which wear and become smaller as the mill is operated. New large balls are added periodically. As the shell of such a mill rotates, 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. The amount of energy expended is suited to the difficulty of the breaking operation, increasing the efficiency of the mill.

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**Check Your Progress Exercise 1**

**Note:** a) Use the space below for your answer.
b) Compare your answers with those given at the end of the unit.
c) Use separate sheets where no space is provided.

1. Enlist the different characteristics of an ideal size reducing machine.

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2. Describe various methods of size reduction with suitable examples.

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3. Classify the size reduction machines according to the methods used.

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4. Write short notes on the following:

   i) Jaw crusher
   ii) Toothed roll crusher
   iii) Hammer mill
   iv) Attrition mill
   v) Tumbling mill

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### 5.4.3 Ultrafine Grinders

Many commercial powders must contain particles averaging 1 to 20 $\mu m$ in size, with substantially all particles passing a standard 325-mesh screen that has openings 44 $\mu m$ wide. Mills that reduce solids to such fine particles are called *ultra fine 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.

**Classifying hammer mills:** 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 chamber the particles of solid are given a high rotational velocity. Coarse particles are concentrated along the wall of the chamber because of centrifugal force acting on them. The air stream 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 further reduction in the grinding chamber. Changing the rotor speed or the size and number of the separator vanes varies the maximum particle size of the product. Mills of this kind reduce 1 or 2 ton/h to an average particle size of 1 to 20 $\mu m$, with an energy requirement of about 40 kWh/metric ton.

**Fluid energy mills:** In these mills the particles are suspended in a high - velocity gas stream. In some designs the gas flows in a circular or elliptical path; in others there are jets that oppose one another or vigorously agitate a fluidized bed. Some reduction occurs when the particles strike or rub against the walls of the confining chamber, but most of the reduction is believed to be caused by interparticle attrition. Internal classification keeps the larger particles in the mill until they are reduced to the desired size.

The suspending gas is usually compressed air or superheated steam, admitted at a pressure of 7 atm through energizing nozzles. 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 near the bottom of the loop through a venturi injector. Classification of the ground particles takes place at the upper bend of the loop. As the gas stream flows around this 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. The classification is aided by the complex pattern of swirl generated in the gas stream at the bend in the loop of pipe.2 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 non sticky solid to particles averaging! to 10 11m 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.

**Agitated mills:** For some ultrafine grinding operations, small batch non rotary mills containing a solid grinding medium are available. The medium consists of hard solid elements such as balls, pellets, or sand grains. These mills are vertical vessels 4 to 1200 L in capacity, filled with liquid in which the grinding medium is suspended. In some designs the charge is agitated with a multiarmed 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 withdrawn through a screen at the bottom. Agitated mills are especially useful in producing particles 1 */lm* in size or finer.

**Colloid mills:** In a colloid mill, intense fluid shear in a high-velocity stream is used to disperse particles or liquid droplets to form a stable suspension or emulsion. The final size of the particles or droplets is usually less than 5 */lm*. Often there is little actual size reduction in the mill; the principal action is the disruption of lightly bonded clusters or agglomerates. Syrups, milk, purees, ointments, paints, and greases are typical products processed in this way. Chemical additives are often useful for stablizing the dispersion.

In most colloid mills the feed liquid is pumped between closely spaced surfaces one of which is moving relative to the other at speeds of 50 m/s or *more.* In the mill shown schematically in Figure 5.9 the liquid passes through the narrow spaces between the disk-shaped rotor and the casing. The clearances are adjustable down to 25 */lm.* Often cooling is required to remove the heat generated. The capacities of colloid mills are relatively low, ranging from 2 or 3 L/min for small mills up to 440 L/min for the largest units.

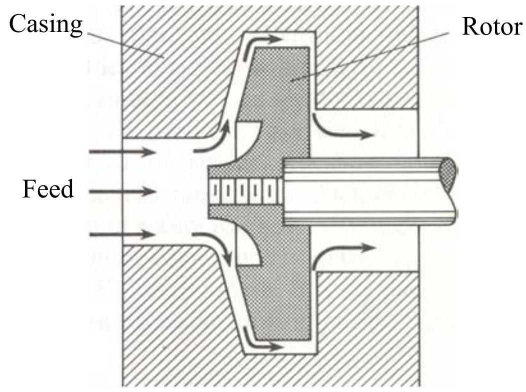


**Figure 5.9: Schematic drawing of colloid mill**

### 5.4.4 Cutting Machines

In some size-reduction problems the feed stocks are too tenacious or too resilient to be broken by compression, impact, or attrition. In other problems 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. The sawtoothed crushers mentioned above do much of their work in this way. True cutting machines include rotary knife cutters and granulators. These devices find application in a variety of processes but are especially well adapted to size reduction problems in the manufacture of rubber and plastics.

**Knife cutters:** A rotary knife cutter, as shown in Figure 5.10, contains a horizontal rotor turning at 200 to 900 r/min in a cylindrical chamber. On the rotor are 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 entering the chamber from above are cut several hundred times per minute and emerge 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.

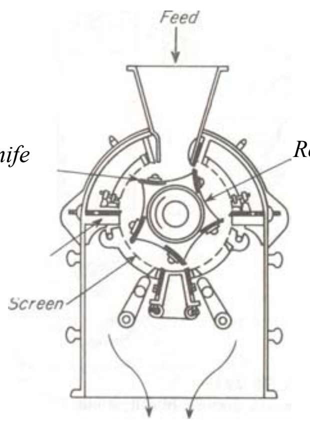


**Figure 5.10: Rotary knife cutter**

## 5.5 EFFICIENCY OF SIZE REDUCTION

The ratio of the surface energy created by crushing to the energy absorbed by the solid is the crushing efficiency, $\eta_c$. If $e_s$ is the surface energy per unit area, in meter times kg force per square meter, and $A_{wb}$ and $A_{wa}$ are the areas per unit mass of product and feed, respectively, the energy absorbed by a unit mass of the material $W_n$ is

$$W_n = \frac{e_s\left(A_{wb} - A_{wa}\right)}{\eta_c} \qquad (5.2)$$

The surface energy created by fracture is small in comparison with the total mechanical energy stored in the material at the time of rupture, and most of the latter is converted into heat. Crushing efficiences are therefore low. Typical crushing efficiencies range between 0.06 and 1 percent.

The energy absorbed by the solid $W_n$ is less than that fed to the machine. Part of the total energy input W is used to overcome friction in the bearings and other moving parts, and the rest is available for crushing. The ratio of the energy absorbed to the energy input is, $\eta_m$, the mechanical efficiency. Then, if W is the energy input,

$$W = \frac{W_n}{\eta_m} = \frac{e_s\left(A_{wb} - A_{wa}\right)}{\eta_m \eta_c} \qquad (5.3)$$

## 5.6 ENERGY REQUIREMENT FOR SIZE REDUCTION

The cost of power is a major expense in crushing and grinding, so the factors that control this cost are important. During size reduction, the particles of feed material are first distorted and strained. The work 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. As additional force is applied to the stressed particles, they are distorted beyond their ultimate strength and suddenly rupture into fragments. 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. By conservation of energy, all energy of stress in excess of the new surface energy created must appear as heat.

If $\dot{m}$ is the feed rate, the power (P) required by the machine is

$$P = W\dot{m} = \frac{\dot{m}e_s\left(A_{wb} - A_{wa}\right)}{\eta_c\eta_m} \tag{5.4}$$

The average particle size of a mixture of particles is defined in several different ways. Probably the most used is the volume-surface mean diameter, $\overline{D}_s$, which is related to the specific surface area $A_w$. It is defined by the following equation

$$\overline{D}_s \equiv \frac{6}{\phi_s A_w \rho_p} \tag{5.5}$$

where $\phi_s$, spehiricity of particle, and

$\rho_p$, density of particle, kg/m$^3$

Substituting $A_{wb}$ and $A_{wa}$ from equation 5.5 in 5.4 we get

$$P = \frac{6\dot{m}e_s}{\eta_c\eta_m\rho_p}\left(\frac{1}{\phi\overline{D}_{sb}} - \frac{1}{\phi\overline{D}_{sa}}\right) \tag{5.6}$$

where $\overline{D}_{sa}$ is mean diameter of feed, and

$\overline{D}_{sb}$ is mean diameter of product

### 5.6.1 Empirical Relationships

**Rittinger's Law:** A crushing law proposed by Rittinger in 1867 states that the work required in crushing is proportional to the new surface created. This "law," which is really no more than a hypothesis, is equivalent to the statement that the crushing efficiency, $\eta_c$, is constant and, for a given machine and feed material, is independent of the sizes of feed Md product. If the sphericities $\phi_a$ and $\phi_b$ are equal and the mechanical efficiency is constant, the various constants in equation (5.6) can be combined into a single constant $K_r$, known as Rittinger's constant and Rittinger's law written as

$$\frac{P}{\dot{m}} = K_r\left(\frac{1}{\overline{D}_{sb}} - \frac{1}{\overline{D}_{sa}}\right) \tag{5.7}$$

**Kick's Law:** In 1885 Kick proposed another "law," based on stress analysis of plastic deformation within the elastic limit, which states that the work required for crushing a given mass of material is constant for the same reduction ratio, that is, the ratio of the initial particle size to the final particle size. This leads to the relation

$$\frac{P}{\dot{m}} = K_k \ln\frac{\overline{D}_{sa}}{\overline{D}_{sb}} \tag{5.8}$$

where $K_k$ is a constant.

A generalized relation for both cases is the differential equation

$$d\left(\frac{P}{\dot{m}}\right) = -\frac{Kd\overline{D}_s}{\left(\overline{D}_s\right)^n} \tag{5.9}$$

Solution of equation (5.9) for $n$ = 1, 2 leads to Kick's law and Rittinger's law, respectively.

Both Kick's law and Rittinger's law have been shown to apply over limited ranges of particle size, provided $K_k$ and $K_r$ are determined experimentally by tests in a machine of the type to be used and with the material to be crushed. They thus have limited utility and are mainly of historical interest.

**Bond Crushing Law and Work Index :** A somewhat more realistic method of estimating ,the power required for crushing and grinding was proposed by Bond in 1952. Bond postulated that the work required to form particles of size $D_p$ from very large feed is proportional to the square root of the surface-to-volume ratio of the product $s_p/v_p$ *and* $s_p/v_p = 6/\phi_s D_p$ , from which it follows that

$$\frac{P}{\dot{m}} = \frac{K_b}{\sqrt{D_p}} \tag{5.10}$$

where $K_b$ is a constant that depends on the type of machine and on the material being crushed. This is equivalent to a solution of equation (5.9) with $n$ = 1.5 and a feed of infinite size. To use equation (5.10), a work index $W_i$ *;* is defined as the gross energy requirement in kilowatt hours per ton of feed needed to reduce a very large feed to such a size that 80 percent of the product passes a *100 μm* screen. This definition leads to a relation between $K_b$ and $W_i$ . If $D_p$ is in millimeters, $P$ in kilowatts, and $\dot{m}$ in tons per hour,

$$K_b = \sqrt{100x10^{-3}}W_i = 0.3162W_i \tag{5.11}$$

If 80 percent of the feed passes a mesh size of $D_{pa}$ millimeters and 80 percent of the product a mesh of $D_{pb}$ millimeters, it follows from equations (5.10) and (5.11) that

$$\frac{P}{\dot{m}} = 0.3162W_i\left(\frac{1}{\sqrt{D_{pb}}} - \frac{1}{\sqrt{D_{pa}}}\right) \tag{5.12}$$

The work index includes the friction in the crusher, and the power given by equation (5.12) is gross power. For dry grinding, the power calculated from equation 5.12 is multiplied by 4/3.

## 5.7 SCREEN ANALYSIS

The most common method of classification of comminuted product is screening of the ground material through set of sieves, which is also called as 'screen analysis.' Bureau of Indian Standards has standardized mesh sizes for screen analysis. The size of openings of standard screens are given in Table 5.1

**Table 5.1: Test sieves and their respective sizes**

| BSS | ASTM | BISS | Width of opening in inches | Width of opening in mm |
|---|---|---|---|---|
| | 4 | 480 | 0.1870 | 4.750 |
| 5 | 6 | 340 | 0.1252 | 3.250 |
| 6 | 7 | 280 | 0.1109 | 2.818 |
| 7 | 8 | 240 | 0.0945 | 2.399 |
| 8 | 10 | 200 | 0.0800 | 2.032 |
| 10 | 12 | 170 | 0.0659 | 1.676 |
| 12 | 14 | 140 | 0.0553 | 1.405 |
| 14 | 16 | 120 | 0.0473 | 1.201 |
| 16 | 18 | 100 | 0.0394 | 1.000 |
| 18 | 20 | 85 | 0.0332 | 0.954 |
| 20 | - | - | 0.0322 | 0.894 |
| 22 | 25 | 70 | 0.0279 | 0.708 |
| 25 | 30 | 60 | 0.0233 | 0.592 |
| 30 | 35 | 50 | 0.0197 | 0.500 |
| 36 | 40 | 40 | 0.0165 | 0.420 |
| 40 | - | - | 0.0158 | 0.401 |
| 44 | 45 | 35 | 0.0133 | 0.351 |
| 48 | - | - | 0.0132 | 0.336 |
| 50 | - | - | 0.0116 | 0.295 |
| 52 | 50 | 30 | 0.0117 | 0.286 |
| 60 | 60 | 25 | 0.0099 | 0.251 |
| 72 | 70 | 20 | 0.0083 | 0.211 |
| 80 | - | - | 0.0073 | 0.186 |
| 85 | 80 | 18 | 0.0070 | 0.177 |
| 100 | 100 | 15 | 0.0060 | 0.157 |
| 120 | 120 | 12 | 0.0049 | 0.124 |
| 150 | 140 | 10 | 0.0041 | 0.104 |
| 170 | 170 | 9 | 0.0035 | 0.089 |
| 200 | 200 | 8 | 0.0030 | 0.075 |
| 240 | 220 | 7 | 0.0025 | 0.064 |
| 300 | 270 | 6 | 0.0021 | 0.053 |
| 325 | - | 5 | 0.0017 | 0.044 |
| 350 | 325 | - | - | 0.044 |
| 400 | - | 4 | 0.0015 | 0.038 |

For determination of average particle size in ground food grains, a set of Bureau of Indian Standard Screens is arranged serially in a stack. For food grain flour analysis, a set of BIS sieves No. 100, 70, 50, 40, 30, 20 and 15 with pan and cover are taken. A sample of 250 g of ground product is dried in an oven to constant weight. The dried sample is placed in the topmost sieve and the set is placed on the sieve shaking machine and shaken for 5 minutes.

## 5.8 FINENESS MODULUS

The fineness modulus indicates the uniformity of grind in resultant product. It is determined by adding the weight fractions retained above each sieve and dividing the sum by 100. An example of determination of fineness modulus is presented below:

Determination of fineness modulus

| BIS sieve No. | Weight of material retained | % material retained | Fineness modulus | Average particle size, mm |
|---|---|---|---|---|
| 100 | 0.0 | $7 \times 0.00 = 0.00$ | | |
| 70 | 2.8 | $6 \times 1.12 = 6.72$ | | |
| 50 | 18.4 | $5 \times 7.36 = 36.8$ | | |
| 40 | 28.7 | $4 \times 1.48 = 45.92$ | $\frac{279.72}{100} = 2.7972$ | $D = 0.135\,(1.366)^{F.M.}$ $= 0.323$ mm |
| 30 | 90.8 | $3 \times 6.32 = 108.96$ | | |
| 20 | 98.5 | $2 \times 39.4 = 78.8$ | | |
| 15 | 6.3 | $1 \times 2.52 = 2.52$ | | |
| Pan | 4.5 | $0 \times 1.80 = 0.00$ | | |
| | | 279.72 | | |

**Check Your Progress Exercise 2**

**Note:** a) Use the space below for your answer.
b) Compare your answers with those given at the end of the unit.
c) Use separate sheets where no space is provided.

1. Write short notes on the following:

   i) Colloid mill,
   ii) Knife cutter.

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2. Define crushing efficiency and mechanical efficiency.

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3. Typical crushing efficiencies vary between ………….. % and ……….. %.

4. Wheat (4.33 mm size) was milled by a burr mill at two different gaps between the burr stones. 250 g of the flour was analyzed by BIS sieves for particle size determination as given below. The power required to mill wheat, at first setting was 8.0 kW.

   Calculate the power requirement of the mill in second setting using (1) Rettinger's law and (2) Kick's law. The capacity of the mill is 0.2 t/hr.

| **BIS sieve No.** | **Mass fraction of flour retained over sieve, g** | |
|---|---|---|
| | **I setting** | **II setting** |
| 100 | – | – |
| 70 | 10.1 | 1.5 |
| 50 | 16.7 | 13.3 |
| 40 | 36.0 | 36.1 |
| 30 | 82.2 | 74.8 |
| 20 | 96.0 | 104.6 |
| 15 | 8.0 | 8.4 |
| Pan | 0.0 | 11.3 |

5. What is screen analysis?

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6. What is fineness modulus?

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## 5.9 LET US SUM UP

We will now recollect the major concepts presented in this unit. Size reduction is an important unit operation to facilitate the processing of food. The four methods of size reduction are crushing, impact, shearing and cutting. A large number of size reducing machines have been developed to meet the specific needs of the raw materials and the food processing. There are two basic parameters which are considered in the design or selection of a size reducing equipment. The first is the energy required for the size reduction. Finer the final particle size, larger will be the energy requirement. Rittinger, Kick, and Bond have proposed different empirical equations for estimating the energy requirement in size reduction. Effort should be made to use one or more of these equations to ensure that the size reduction operation is being carried out efficiently. The other basic parameter is the quality of the final product which is expressed in terms of particle size distribution. Fine mass modulus is computed from the particle size distribution obtained from screen analysis of the final product. It indicates the uniformity of the particle sizes in the final product.

## 5.10 KEY WORDS

**Size reduction/ Comminution** : The term *size reduction* is applied to all the ways in which particles of solids are cut or broken into smaller pieces.

**Crushing** : When an external force applied on a material excess of its strength, the material fails because of its rupture in many directions.

**Impact** : When a material is subjected to sudden blow of force in excess of its strength, it fails, like cracking of nut with the help of a hammer.

**Shearing** : It is a process of size reduction, which combines cutting and crushing. The shearing units consist of a knife and a bar.

**Cutting** : It is a method of size reduction accomplished by forcing a sharp and thin knife through the material.

**Grinders** : The term *grinder* describes a variety of size-reduction machines for intermediate duty. The product from a crusher is often fed to a grinder, in which it is reduced to powder.

**Rittinger's law** : A crushing law proposed by Rittinger in 1867 states that the work required in crushing is proportional to the new surface created.

**Kick's law** : It is based on stress analysis of plastic deformation within the elastic limit, which states that the work required for crushing a given mass of material is constant for the same reduction ratio, that is, the ratio of the initial particle size to the final particle size.

**Crushing efficiency** : It is the ratio of the actual and the theoretical energy requirement for crushing a material into a given size multiplied by 100.

**Screen analysis** : Is the most common method of classification of comminuted product obtained using screening of the ground material through set of sieves.

**Fineness modulus** : The fineness modulus indicates the uniformity of grind in resultant product. It is determined by adding the weight fractions retained above each sieve and dividing the sum by 100.

## 5.11 ANSWERS TO CHECK YOUR PROGRESS EXERCISES

**Check Your Progress Exercise 1**

1. i) large capacity,
   ii) should yield a predesired sized product or range of size,
   iii) small power input requirement per unit of product handled, and
   iv) easy and trouble free operation.

2. Solids may be broken in many different ways, but only four of them are commonly used in size-reduction machines:

   i) *compression, e.g. a nutcracker:* Application of external force in excess of the material strength. The particles produced after crushing are irregular in shape and size.

   ii) *impact, e.g. a hammer:* Material is subjected to sudden blow of force in excess of its strength, which causes rupture.

   iii) *attrition, or rubbing, e.g. a file:* It combines cutting and crushing. The shearing units consist of a knife and a bar. If the edge of knife or shearing edge is thin enough and sharp, the size reduction process nears to that of cutting, whereas a thick and dull shearing edge performs like a crusher.

   iv) *cutting. e.g. a pair of scissors:* Accomplished by forcing a sharp and thin knife through the material. In the process minimum deformation and rupture of the material results and the new surface created is more or less undamaged.

3. Size-reduction equipment are: crushers, grinders, ultrafine grinders, and cutting machines.

   They work on the methods of compression, impact, attrition, or rubbing, and cutting. Compression is the characteristic action of crushers. Grinders employ impact and attrition, sometimes combined with compression; ultrafine grinders operate principally by attrition. A cutting action is of course characteristic of cutters, dicers, and slitters.

4. i) *Jaw crusher:* In a jaw crusher feed is admitted between two jaws, set to form a V open at the top. The jaws open and close 250 to 400 times per minute.

   ii) *Toothed roll crusher:* The particle size of the feed to these machines may be as great as 500 mm; their capacity ranges up to 500 tons/h.

   iii) *Hammer mill:* These mills all contain a high-speed rotor turning inside a cylindrical casing. The shaft is usually horizontal Feed dropped into the top of the casing is broken and falls out through a bottom opening.

   iv) *Attrition mill:* In an attrition mill particles of soft solids are rubbed between the grooved flat faces of rotating circular disks. The axis of the disks is usually horizontal, sometimes vertical.

   v) *Tumbling mill:* A cylindrical shell slowly turning about a horizontal axis and filled to about half its volume with a solid grinding medium forms a tumbling mill. For intermediate and fine reduction of abrasive materials tumbling mills are unequaled.

**Check Your Progress Exercise 2**

1. i) *Colloidal mill:* In a colloid mill, intense fluid shear in a high-velocity stream is used to disperse particles or liquid droplets to form a stable suspension or emulsion. The final size of the particles or droplets is usually less than 5 */lm.* The principal action is the disruption of lightly bonded clusters or agglomerates.

   ii) *Knife cutter:* A rotary knife cutter, as shown in Fig. 5.10, contains a horizontal rotor turning at 200 to 900 r/min in a cylindrical chamber. On the rotor are 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 entering the chamber from above are cut several hundred times per minute and emerge at the bottom through a screen with 5 to 8 mm openings.

2. Crushing efficiency $\eta_c$ is the ratio of the surface energy created by crushing to the energy absorbed by the solid whereas mechanical efficiency $\eta_m$ is the ratio of the energy absorbed to the energy input to any size reduction machine.

3. 0.06 % and 1%.

4. Determination of flour sizes of two setting by sieve analysis:

i) Average particle size of product in I setting:

| BIS sieve No. | Weight of material retained | % material retained | Fineness modulus | Average particle size, mm |
|---|---|---|---|---|
| 100 | 0.0 | $7 \times 0.00 = 0.00$ | $\frac{295.08}{100} = 2.9508$ | $D = 0.135\,(1.366)^{F.M.}$ $= 0.338$ mm |
| 70 | 10.1 | $6 \times 4.04 = 24.24$ | | |
| 50 | 16.7 | $5 \times 6.68 = 33.40$ | | |
| 40 | 36.0 | $4 \times 14.40 = 57.60$ | | |
| 30 | 83.2 | $3 \times 33.28 = 99.84$ | | |
| 20 | 96.0 | $2 \times 38.40 = 76.80$ | | |
| 15 | 8.0 | $1 \times 3.20 = 3.20$ | | |
| Pan | 0.0 | $0 \times 0.00 = 0.00$ | | |
| | | 295.08 | | |

ii) Average particle size of product in II setting:

| BIS sieve No. | Weight of material retained | % material retained | Fineness modulus | Average particle size, mm |
|---|---|---|---|---|
| 100 | 0.0 | $7 \times 0.00 = 0.00$ | $\frac{264.76}{100} = 2.6476$ | $D = 0.135\,(1.366)^{F.M.}$ $= 0.308$ mm |
| 70 | 1.5 | $6 \times 0.60 = 3.60$ | | |
| 50 | 13.3 | $5 \times 5.32 = 26.60$ | | |
| 40 | 36.1 | $4 \times 14.44 = 57.76$ | | |
| 30 | 74.8 | $3 \times 29.92 = 89.76$ | | |
| 20 | 104.6 | $2 \times 41.84 = 83.68$ | | |
| 15 | 8.4 | $1 \times 3.36 = 3.36$ | | |
| Pan | 11.3 | $0 \times 4.52 = 0.00$ | | |
| | | 264.76 | | |

Determination of Power Requirements:

i) According to Rettinger's Law

$$\frac{P}{\dot{m}} = K_r\left(\frac{1}{\overline{D}_{sb}} - \frac{1}{\overline{D}_{sa}}\right)$$

or $$\frac{8.0}{0.2} = K_r\left(\frac{1}{0.338} - \frac{1}{4.33}\right)$$

or $40 = K_r \times 2.7276$

or $K_r = 14.6649$

Putting the value of $K_r$ in II setting,

$$\frac{P}{0.2} = 14.6649\left(\frac{1}{0.308} - \frac{1}{4.33}\right)$$

or $\quad P = 0.2 \times 14.6649 \times 3.0157 = 8.85$ kW

ii) According to Kick's Law

$$\frac{P}{\dot{m}} = K_k \ln \frac{\overline{D}_{sa}}{\overline{D}_{sb}}$$

or $\quad \dfrac{8.0}{0.2} = K_k \ln \dfrac{4.33}{0.338}$

or $\quad K_k = 15.6846$

Putting the value of $K_k$ in II setting,

$$\frac{P}{0.2} = 15.6846 \ln \frac{4.33}{0.308}$$

or $\quad P = 8.2916$ kW

5. Screen analysis is a method of classification of comminuted product by screening of the ground material through set of standard sieves.
6. The fineness modulus is an indicator of the uniformity of grind in the resultant/final product. It is determined by adding the weight fractions retained above each sieve and dividing the sum by 100.

## 5.12 SOME USEFUL BOOKS


1. Henderson, S.M. and Perry, R.L. (1976) Agricultural Process Engineering. AVI Publishing Co. West Port Connecticut.
2. McCabe, W.L., Smith, J.C. and Harriott, P. (1993) Unit Operations of Chemical Engineering. McGraw Hill, New York.