GRINDING & MIXING

Both Grinding and Mixing come under the broad category of Mechanical operations. Mechanical operations are physical operations without mass transfer with mechanical energy as driving force. Let us take up Grinding first.

Grinding

Grinding comes under the unit operation of Size reduction under Mechanical operations. This is a popular chemical engineering unit operation which finds applications even in food processing. Unit operation is an operation which cannot be reduced further into any sub-operations, in a given over all process. For example, making coffee extract (decoction) involves several unit operations such as harvesting beans, fermenting, drying, grinding and extraction to obtain decoction.

Let us study the following aspects of Grinding.

1. Definition.
2. Objectives of Grinding
3. Types of actions involved in Grinding
4. Factors affecting Grinding efficiency
5. Equivalent diameter – Sphericity
6. Energy laws governing Grinding
7. Equipment for Grinding

   and finally
8. Applications in Food Processing

1. Definition

Grinding is defined as a size reduction operation of any given raw material prior to subjecting to food processing operations.

2. Objectives of Grinding

The major objectives of grinding operation are to increase the reactivity, to remove unwanted material, to increase mass transfer, to facilitate storage, transport and also further processing. For instance, in mango processing the skin and center stone are not edible portions as such. Hence, they will be removed by size reduction operation called pulping. Size reduction increases the surface area, and reduces diffusional distance there by increases mass transfer.

Let us look at the relevance of this unit operation to food processing with the help of some examples. Consider the de-hulling and polishing of paddy. De-hulling of paddy is carried out in hullers or roller mills to get rice. However, Brown rice (just de-hulled rice) has issues such as poor cooking as well as sensory quality and poor storage. Accordingly, it has to be polished to partially or completely remove the bran to obtain under-polished rice or white rice. Grinding is popular for producing spice powders say turmeric, pepper, chilly etc., after primary cleaning. It may be noted that many volatiles are lost from these spices during grinding operation due to the frictional heat produced during grinding. To retain these volatiles, fetching higher price, grinding is carried out at low temperatures achieved by liquid nitrogen, popularly known as Cryogrinding. Liquid nitrogen makes the spices brittle, especially ones like ginger, turmeric, even coconut etc., facilitating the size reduction.

3. Types of actions/forces involved in Grinding

Let us look at the basic types of forces in size reduction equipments are Compression, Impact, Attrition and Cutting.

Compression involves gradual application of force (pressure) Example: Areca nut cracker.

Impact involves sudden application of force and requires sieves to separate ground material into fractions of different particle sizes. Example: Hammer mill.

Attrition involves application of shear force (rather than pressure) resulting in a very fine powder. Example: Disc mill.

Cutting involves application of force over a small area resulting in particles of defined size and shape. Example: Slicer/Dicer.

4. Factors affecting Grinding efficiency

Density of raw material – Higher the density higher is the production rate and energy consumption. Materials with low bulk density leads to low production rate and low power consumption).

Moisture content – The fracture stress of the material varies with the moisture content in the raw material. Example: house hold grinding of rice or *ragi* is carried out by soaking, draining excess water and shade drying prior to grinding. It enables to get nice flour as the residual moisture absorbs the frictional heat, leaving the flour dry and free flowing.

Temperature – Lower temperatures facilitate the grinding of heat sensitive material. Example: Wax, chocolate, cocoa butter, fat powders.

5. Equivalent diameter – Sphericity

Shape and Size of the particles obtained on size reduction will not be uniform. Some will be close to cylindrical shape and some to spherical shape. It is desirable to know the closeness of the particles to that of a standard sphere, which is expressed as equivalent diameter and known as Sphericity (ϕ_s).

It is defined as the ratio of surface-to-volume of a sphere to that ratio of actual surface-to-volume of the given particle.
From geometry we know the equation for

$Sp = \pi Dp^2$

$Vp = (1/6)\pi Dp^3$

$$\phi_S = \{(Sp/Vp)_{sphere}\}/\{(Sp/Vp)_{particle}\}$$
$$= (6/Dp)/(Sp/Vp)\ particle$$
$$= (6\ V_{particle}) / (DpS_{particle})$$

Dp is obtained by equating the actual volume of the particle to that of a sphere.

6. Energy laws governing Grinding

Grinding is one of the most energy intensive unit operations. Out of the energy supplied only 2 % is utilized for the size reduction, in other words for the creation of new surface and rest is dissipated as frictional heat energy.
The design of equipment is empirical in nature based on the empirical laws which are discussed below.

Rittinger's law

It is proposed on the basis that the energy consumption is inversely proportional to the area created. In the differential form.

$$\mathbf{(dE/dL) = - C (L)^{-P} = - C (L)^{-2}}.$$

The equation can be integrated as (dL negative sign for size reduction, P= -2 for being inversely proportional to area)

$$\mathbf{E = C [(1/L_2) - (1/L_1)]}$$

where **C**= $\mathbf{K_R}$ $\mathbf{f_C}$; $\mathbf{K_R}$ is Rittinger's constant. $\mathbf{f_C}$ is a constant which accounts for the crushing strength of the material. It may be noted that the constants are dimensional.

Rittinger's law holds good for grinding operation (rather than crushing operation) that is, size reduction from medium to small size particles. According to this equation, the crushing efficiency is constant for a given machine and material. It is independent of the size of the feed and the final product. These are the drawbacks of this law.

Kick's law

Instead of surface area alone, this equation proposes surface area per unit mass.

(Surface area/mass) = $(L^2/M) = (L^2/L^3) = (L^{-1})$. In other words P = -1

$$(dE/dL) = -C(L)^{-P} = -C(L)^{-1}.$$

On integration, it gives

E = Cln (L_1/L_2) where **C = $K_K f_C$**

Kick's law holds good for coarse crushing operation (from large to medium size).

Further, energy requirement is independent of feed and product sizes as long as reduction ratio is maintained the same. These are the drawbacks of this law.

Bond's law

Intermediate situation is proposed by this law and accordingly P = -3/2

$(dE/dL) = -C(L)^{-P} = -C(L)^{-3/2}$, on integration

$$E = 2C\left[\sqrt{\left(\frac{1}{L_2}\right)} - \sqrt{\left(\frac{1}{L_1}\right)}\right]$$

7. Equipment for Size Reduction - Grinding/Crushing

In comparison with other unit operations, Grinding/Crushing remained still an art and slowly marching towards science. Excellent equipment is being designed despite the lack of a single general theory, mostly based on experimental data generated and by extrapolation. Equipment is available for chemical industries are being adopted for food processing industry. Let us attempt for citing maximum food applications to make the topic relevant and interesting.

Among the types of forces discussed above, one of them will be predominant force in each of the equipment described below. However, some contribution of remaining forces cannot be avoided completely.

a. Crushers

Jaw crusher

As the name suggests (figure), one jaw is fixed while the other is mobile or swinging with an inclined surface (like human jaws) and the crushing angle is about 27 ^{o}. Thus it has 'V' opening for the feed. The major force involved is compression. The frequency of the swinging jaw is about 250-400 times/minute. The average opening for the feed is 1.0 - 2.5 m, taking about the feed of size around 1.5 m. The crushing capacity is about 1000-1200 tons/hour.

Gyratory crusher

By virtue of the shape of the holding chamber and crushing head (figure), the 'V' shape crushing zone exits at one location or the other at any given time and gives around 100-400 gyrations per minute. As a result it gives higher capacity (about 4500 tons/hour). Being a crusher, the major force/action involved is compression. Consumes lesser power consumption and lower maintenance when compared to jaw crusher.

Other types

Other types of crushers include smooth roller crusher, Single roll toothed crusher as can be seen from the figures.

b. Grinders

Hammer mill

It has a high speed rotor in a cylindrical casing and can grind almost anything (Figure). The rotor has rigid or swing hammers mounted on it. The major force/action involved is 'Impact'. Due to the high impact cell disruption is more, giving a wet ground material say ginger or coconut grating.

It is provided with a sieve to control the particle size of the product. Used for grinding of wheat as different varieties of flours are required for making different types of breads. Also used for the grinding of de-oiled cake, which is rich in fiber and protein.

c. Attrition mills

Disc mill

The size reduction occurs by a single rotating disc against a stationary disc. The major force/action involved is 'shear or attrition". The burr stone or rock emery is being replaced with Stainless steel disks to cater to the food safety regulation standards.

The rotating disc can be cooled by brine or refrigerant. Air is drawn into the system in order prevent choking of the equipment. Disk mills are suitable for soft materials such as spices (pepper, cumin, ajwaine etc.), Capacity in the range 0.8 to 8 tons/hour. Required size is obtained by adjusting gap/space between the discs and by multiple passes through the equipment.

Ball mill

This is also known as one type of tumbling mill. This unit can be operated both on batch or continuous mode (Figure). Solid metal spheres of different sizes occupy almost half the volume of the conical casing of the equipment. The major force/action involved is ‘attrition’ between material and spherical metal balls and also the ‘Impact’ of the metal balls as they fall during rotation.

Other types

The other types are mainly ultrafine grinders such as fluid energy mill, agitated mills and colloid mill etc. as can be seen in the figures. In all of these the major force/action involved is ‘attrition’. For example: colloid mill is suitable for stabilization of coconut milk emulsion prior to spray drying and for breakage of algal cells for the release of secondary metabolites such as proteins.

d. Cutting machines

Fruits and vegetables are not suitable for compression, impact or attrition. It is often required to produce pieces of fixed dimensions and shapes from them for specific applications.

Knife cutter

It has a rotor with knifes, rotating while having small clearance with a stationary set of knives. Material is cut several times per minute into product of uniform size, say cubes of 5-8 mm, or discs of 1-2 mm thickness and diameter 4-8 cm.

Examples include Cubes of raw or mature papaya for tooty-fruity ice cream. Pine apple slices for canning in sugar syrup or juice itself, rectangular long cubes of potato for the famous ‘French fries’ etc.

8. Applications in Food processing

In addition to the examples cited till now, Wheat milling is a very big industry for the production of flours of different particle sizes for different products. Preprocessing of coconut such as de-shelling, paring to remove testa, production of coconut grating, de-shelling of cashew nuts, de-husking of sunflower seeds prior to expelling of oil, de-skinning of pine apple are a few.

MIXING

Mixing is a unit operation which finds its place in several processes including food processing operations. One should distinguish mixing from agitation. Agitation is providing motion in a homogeneous phase (gas / liquid or even a solid phase). On the other hand, mixing involves more than one phase which is to be thoroughly distributed into each other or one another with good degree of uniformity throughout the system. For instance, water can be agitated and alcohol will be mixed with water along with some solids.

The following aspects need to be studied with regard to grinding.

1. Definition
2. Objectives of Mixing.
3. Design of equipment

1. Definition

Mixing is an unit operation for blending more than one component and more than one phase thoroughly to achieve a uniform distribution.

2. Objectives of agitation/ Mixing

It could be simply the heat transfer (heating or cooling). It could be for blending one liquid into other. For mixing two solids such as asafetida with filler material such as flour. Also for suspension of solids in liquid or dispersion of gas in liquid (fermentation).

3. Design of equipment

The equipment design is very crucial for achieving the desirable degree of mixing or end result in a given processing operation. These mixing equipment find application in different processing operations such as crystallization, solid dissolution, preparation of squashes and jams etc. The mixing equipment has a tank, impeller, baffles and motors. There will be provision for addition of acid/ base/ flavor and also to drain the contents.

The tank volume (size) will be decided by the capacity of the given process operation. Once working volume is predetermined, the tank diameter (T) and height (H) of the tank will be fixed.

As a rule of thumb it will be fixed as $H/T=1.0$.

Impeller that generates the liquid current (fluid flow) is the most important component. These impellers can be broadly divided as radial flow and axial flow impellers. Paddles and disc turbines are radial impellers. The flow generated by these impellers will be mainly in the radial direction (the impeller tip to tank wall) Pitched blade turbines and propellers are axial impellers. The flow generated by these is essentially axial (from impeller tip to tank bottom). Some components of radial flow, proportional to the blade width, cannot be avoided. The flow generated by these impellers either in radial or axial direction, eventually returns to the impeller region.

Paddle consumes the highest power since the blade surface area exposed to liquid is the highest in this design of impeller (Power number $N_P=8$). The energy efficiency was improved by incorporating a disc to which small blades are welded in disc turbine ($N_P=5.0$). Power consumption was further improved without compromising in the performance in pitched blade turbine ($N_P=1.2$).

It may be noted that the radial impellers produce more turbulence in the impeller region and as a result most of energy is dissipated in this region without contributing to the actual performance.

As per rule of thumb, the diameter of the impeller (D) is kept as T/3. Clearance of the impeller from the tank bottom is another important parameter that has impact on power consumption as well as performance. Closer to the tank bottom, better will be the performance in terms of fluid flow developed. But power consumption increases with a decrease in clearance from tank bottom. Rule of thumb indicates the impeller clearance(C) as T/3.

Baffles are incorporated in the tank to reduce swirling action and vortexing. Higher the number of baffles, higher will be the impact but higher will be the power consumption. Similarly, higher the width of baffles, higher will be the effect and again higher will be the power consumption. Rule of thumb says the width of baffles (W) is T/10 and number of baffles (N) is 4.

So the standardized design can be summarized as.

D=T/3; C=T/3; W=T/10 and N=4

All these impellers work best for Newtonian fluids. For non- Newtonian flows (whose viscosity will be higher) the impellers namely, helical ribbon, gate impeller, anchor are used.

The dimensionless number called Reynolds number (Re) defines the nature of flow whether it is a laminar flow or turbulent flow. Reynolds number gives the ratio of inertial force to the viscous force.

Re = Inertial force/ Viscous force

In a flow through tubes it is given as

$$Re=D\vartheta\rho/\mu$$

where 'D' is tube diameter, ϑ is velocity of the fluid (gas or liquid), ρ is density of the fluid and μ is the viscosity.

In case of impeller, ϑ (the impeller speed) which is equal to nD (n= impeller rotational speed, rpm). Accordingly, the Re takes the form as.

$$R = \left[\frac{(nD)D\rho}{\mu}\right] = \frac{nD^2\rho}{\mu}$$

The power consumption has strong dependency on the impeller diameter and rotational speed for a given fluid and is given by

$$P = N_p \rho n^3 D^5$$

For a flow (Q) produced by the impeller

$$Q = W_Q D^3$$

where $W_{Q=}$ Pumping capacity or flow number

Mixing of solids

Often in food processing mixing of solids is required. For example for preparing ready dry mix powders for different snack foods (such as idly, dosa etc.), for energy food formulations etc. Mixing of solids resembles mixing of low viscosity liquids. Hence, the same equipment used for liquids can be used for blending solids as well. Yet the mixing operation will be significantly different from liquids in the sense that there will not be any flow pattern in solid mixing. More power is required when compared to liquids. Uniformity of the mixing is ensured by collecting good number of samples from different locations of the mixing equipment. The sample size has to be reasonable large to get consistent results.

The equipment for mixing of free flowing solids includes Ribbon mixer/ blender, axial mixer, tubular mixer (Figure). Ribbon mixer contains as suggested by name two helical ribbons (one big and one small) intervened with each other. It is used for mixing of small portions of solids (or liquids) into large quantity of solids. Axial mixers will also have helical screws which provide good radial mixing and axial moment of material (plug flow). The screw gyrates in the conical casing meeting all locations of equipment. The tumbler mixer resembles a cement concrete mixer. Different configurations with twin shell or double cone are available. Even the ball mill without metal spheres can be used as solids mixer. Entoleter is a centrifugal mixer used for fortification Atta with micro nutrients.