FOOD POWDER PROCESSING

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Contents

Summary

Process and design aspects of unit operations involving particulate solids applied to foods are discussed. Theoretical considerations, operating principles, and applications of different techniques used to process powders in the food industry are reviewed. This

industry needs to make its processing operations more efficient in order to contribute to a better human environment. In this sense, future competitiveness may be critically dependent on knowledge originating from research activities on particle technology, as food processing involves a great number of raw materials and products in particulate form. This article attempts to provide criteria and information for students, academics, and industrialists, who may perceive that future growth in this strategic industry may be dependent on a deeper understanding of particle technology.

1. Introduction: Applied Powder Technology to Food Materials

The food processing industry is one of the largest manufacturing industries in the world. Undoubtedly, it possesses a global strategic importance and, as such, has a critical need for growth based on future research determined by an integrated interdisciplinary approach to problems in food process engineering. Due to relevant recent developments in instrumentation and measuring techniques, a biophysical understanding of foods is advancing rapidly. Detailed study on the physical properties of foods has revealed their important impact on food processes. Among these properties, those related to bulk particulate systems, such as particle size distribution and particle shape, are directly involved in an important number of unit operations (e.g., size reduction, mixing, agglomeration, dehydration, and filtration). The optimum operation for many food processes relies heavily on a good knowledge of the behavior of particles and particle assemblies, either in dry form or as suspensions.

There is a relatively new branch of science and engineering known as Powder Technology or Particle Technology, which deals with the organized study of particulate systems in a broad sense. In the case of food products and materials, some important applications of powder technology can be mentioned. For example, particle size in wheat flour is an important factor in the functionality of food products: attrition of instant powdered foods reduces their reconstitutability, uneven powder flow in extrusion hoppers may affect the rheology of the paste, and appropriate characterization of fluid-particle interactions could optimize clarification of juices.

Research efforts have recently shown tremendous growth. European and Asian professional associations and societies have recognized the importance of powder technology for some time. Some of these associations, such as the Institution of Chemical Engineers (IChemE) and the Society of Chemical Industry (SCI) in the United Kingdom, include well established research groups on the topic and organize meetings and conferences on a regular basis. In the United States, it was not until 1992 that a division known as the Particle Technology Forum was formed within the American Institute of Chemical Engineers (AIChE). This forum has also organized meetings from 1994 to date with a good deal of success. In a more global context, diverse associations worldwide have organized as many as three congresses on particle technology. The last of the series, the *World Congress on Particle Technology 3*, was held in Brighton, UK in 1998, with more than 800 delegates from around the globe attending to present the most advanced developments in the area.

Regarding powder and particle technology applied specifically to food materials, there has not been as much activity as that applied to the inert materials discussed above. The main conferences/ meetings of professional associations and societies related to food processing do not normally include sessions on food powders. These include the Institute of Food Technologists (IFT) in the United States, the Institute of Food Science and Technology (IFST) in the United Kingdom, and the global International Union of Food Science and Technology (IUFoST). Some isolated efforts have been made to promote the exchange of ideas among powder technologists with an interest in food and biological materials. For instance, sessions on food powders were included in the conference known as *Food Ingredients Europe* in 1993 and in the *26th Annual Meeting of the Fine Particle Society* in 1995. With contributions from the latter, a special issue of the journal, *Food Science and Technology International*, was published in 1997.

This article reviews powder technology as applied to food materials. Similar to other process industries, the food industry deals with a great number of raw materials and products in powdered or particulate form. Theoretical and application principles of food powder processing will be discussed in an effort to provide basic tools to improve knowledge and understanding of this focused discipline.

2. Comminution

2.1. Principles of Size Reduction; Properties of Comminuted Products

Many food processes frequently require the reduction in size of solid materials for different purposes. For example, size reduction may aid other processes, such as expression and extraction, or may shorten heat treatments, as in blanching and cooking. Comminution is the generic term used for size reduction and includes different operations such as crushing, grinding, milling, mincing, and dicing. Most of these terms are related to a particular application, for example, milling of cereals, mincing of beef, dicing of tubers, or grinding of spices. The reduction mechanism deforms the piece of food until it breaks or tears. Breaking of hard materials along cracks or defects in their structure is achieved by applying diverse forces. The types of forces commonly used in food processes are compressive, impact, attrition or shear, and cutting.

Compressive forces are used for coarse crushing of hard materials. Coarse crushing implies reduction in size to about 3 mm. Impact forces can be regarded as general purpose forces and may be associated with coarse, medium and fine grinding of a variety of food materials. Shear or attrition forces are applied in fine pulverization, when size of the product reaches the micrometer range. Sometimes the phrase ultra-fine grinding is associated with processes in which a sub-micron range of particles is obtained. Finally, cutting gives a definite particle size and may even produce a definite shape.

As stated earlier, the breakdown of solid material is done through the application of mechanical forces that attack fissures present in the materials original structure. These stresses have been traditionally used to reduce the size of hard materials, from either inorganic (e.g., rocks and minerals) or organic origin (e.g., grains and oilseeds). In such cases, comminuted particles obtained following any size reduction operation will resemble polyhedrons with nearly plane faces and sharp edges and corners. The number of major faces may vary, but is usually between 4 and 7. A compact grain with several nearly equal faces can be considered spherical, so the term diameter is normally used to describe particle size in these comminuted products.

The predictable shapes of products described above have to do with molecular structure, since silicon and carbon, elements of the same group in the periodic table, are generally key components of the crystal units that form the solid matrix. In this sense, a good number of food materials will present the hardness associated with the rigid structure of carbon derivatives and, as such, will fragment following the same pattern of their relatives in the inorganic world whose structure is due to the presence of silicon components. An ideal size reduction pattern to achieve a high reduction ratio of hard brittle food materials, such as sugar crystals or dry grains, could be obtained first by compressing, then by using impact force, and finally by shearing or rubbing. Therefore, only these hard brittle food materials would produce powders when subjected to different forces in a comminution operation, whereas tough ductile food materials, such as meat, can only be reduced in size by applying cut forces. In fact, cutting is considered a process totally different from comminution because its operating principles are quite different from those governing the size reduction of hard materials.

In a comminution operation of food materials, more than one type of the above-described forces is actually present. Regardless of uniformity of the feed material, the product always consists of a mixture of particles covering a range of sizes. Some size reduction equipment is designed to control the size of the largest particles in the products, but the finer sizes are not under control.

In spite of the hardness of the comminuted materials, the above-mentioned shapes of produced particles would be subjected to attrition, due to inter-particle and particle-equipment contacts within the dynamics of the operation. Thus, particle angles will gradually become smooth with the consequent production of fines. In practice, any feed material will possess an original particle size distribution, while the obtained product will end up with a new particle size distribution having a whole range finer than the feed distribution.

Product specification will commonly require that a finished product not contain particles greater than (or smaller than, depending on the application) some specified size. In comminution practice, particle size is often referred to as screen aperture size (Section 5.1). The reduction ratio, defined as the relationship between average size of feed and average size of product, can be used as an estimate of performance of a comminution operation. The values for average size of feed and product depend on the method of measurement, but the true arithmetic mean, obtained form screen analyses on samples of the feed and product streams, is commonly used for this purpose. Reduction ratios depend on the specific type of equipment.

As a rule, the coarser the reduction, the smaller the ratio. For example, coarse crushers have size reduction ratios of below 8: 1, while fine grinders may present ratios as high as 100: 1. However, large reduction ratios, such as those obtained when dividing relatively large solid lumps into ultra-fine powders, are normally attained through several stages using diverse crushing and grinding machines. A good example of this is in the overall milling of wheat grain into fine flour, in which crushing rolls in a series of decreasing diameters are employed.

2.2. Energy Requirements: Comminution Laws

As previously discussed, in the breakdown of hard and brittle solid food materials, two stages of breakage are recognized: (1) initial fracture along existing fissures within the structure of the material, and (2) formation of new fissures or crack tips followed by fracture along these fissures. It is also accepted that only a small percentage of energy supplied to the grinding equipment is actually used in the breakdown operation. Figures of less than 2 percent efficiency have been quoted and, thus, grinding is a very inefficient process, perhaps the most inefficient of traditional unit operations. Much of the input energy is lost in deforming the particles within their elastic limits and through inter-particle friction. A large amount of this wasted energy is released as heat, which in turn may be responsible for heat damage of biological materials.

Theoretical considerations suggest that the energy required to produce a small change in the size of unit mass of material is expressed as a power function of the material size:

$$\frac{dE}{dx} = -\frac{K}{x^n} \qquad (1)$$

where dE is the change in energy, dx is the change in size, K is the constant, and x is the particle size.

Equation (1) is often referred to as the general law of comminution and has been used by a number of workers to derive laws more specific, depending on the application. For example, in the grinding of solids, Rittinger considered that the energy required should be proportional to the new surface produced, and gave the power n a value of 2, thus by integrating Equation (1) obtained the so-called Rittinger's law:

$$E = K\left[\frac{1}{x_2} - \frac{1}{x_1}\right] \qquad (2)$$

where E is the energy per unit mass required for the production of a new surface by reduction, K is called Rittinger's constant and is determined for a particular equipment and material, x_1 is the average initial feed size, and x_2 the average final product size. Rittinger's law has been found to hold better for fine grinding, where a large increase in surface results.

Kick considered that the energy required for a given size reduction was proportional to the size reduction ratio, and gave the power n a value of 1. Thus, by integration of Equation (1), the following relationship, known as Kick's law is obtained:

$$E = K\left[\ln\frac{x_1}{x_2}\right] \qquad (3)$$

where x_1/x_2 is the size reduction ratio. Kick’s law has been found to hold more accurately for coarser crushing, where most of the energy is used in causing fracture along existing cracks.

A third version of the comminution law is the one attributed to Bond, who considered that the work necessary for reduction was inversely proportional to the square root of the size produced. In Bond’s consideration, n has a value of 3/2, yielding the following version (Bond’s law), also by integrating Equation (1):

$$E = 2K\left[\frac{1}{\sqrt{x_2}} - \frac{1}{\sqrt{x_1}}\right] \quad (4)$$

When x_1 and x_2 are measured in micrometers and E in kWh/ton, K=5E$_i$, where E_i is the Bond Work Index, which is defined as the energy required to reduce a unit mass of material from an infinite particle size to a size where 80 percent passes through a 100 micrometer sieve. Bond’s law holds reasonably well for a variety of materials undergoing coarse, medium, and fine size reduction.

2.3. Size Reduction Equipment: Features and Operation

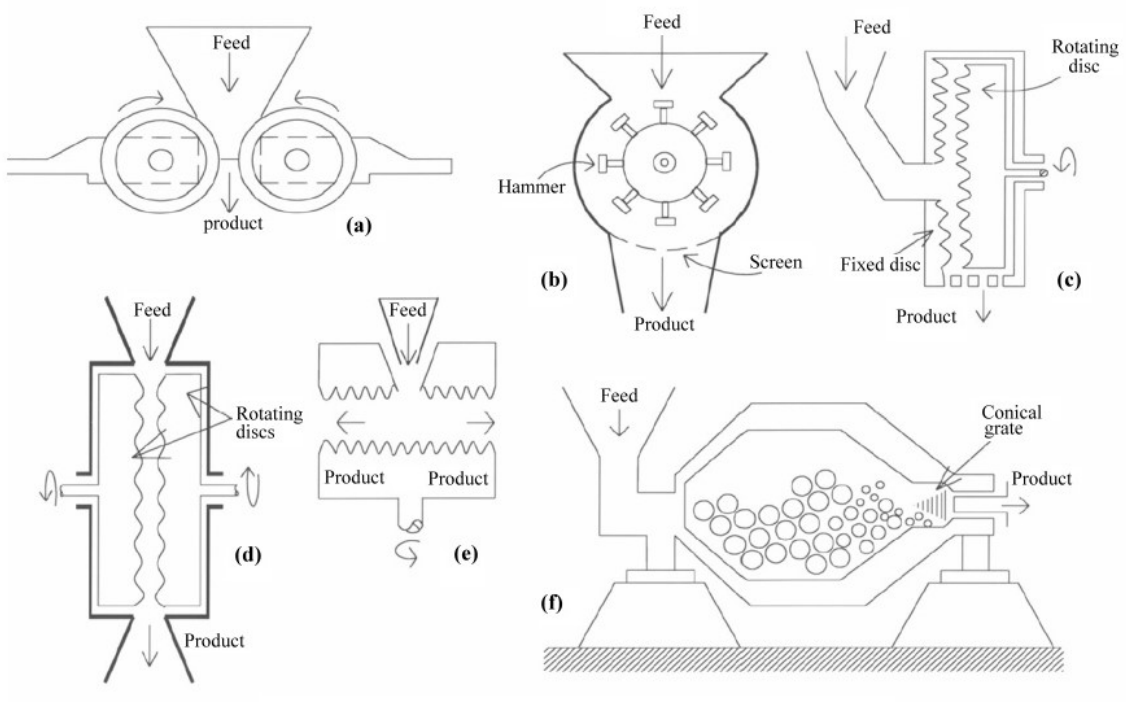

Figure 1. Size reduction equipment used in food processing.

As previously discussed, size reduction is a unit operation widely used in a number of processing industries. Many types of equipment are used in size reduction operations. In a broad sense, size reduction machines may be classified as crushers used mainly for coarse reduction, grinders employed principally in intermediate and fine reduction, ultra-fine grinders utilized in ultra-fine reduction, and cutting machines used for exact reduction. The equipment is generally known as a crusher when performing coarse reduction, and milling when used for all other applications. The above-mentioned classification includes several categories for each type of machine, so in total a number of approximately 20 different designs are recognized in comminution processes. In the food industry, not all equipment has important applications. Figure 1 shows the principal size reduction machines used in food processing.

In *crushing rolls*, two or more heavy steel cylinders revolve towards each other (Figure 1a) so that particles in feed are nipped and pulled through. The nipped particles are subjected to a compressive force that causes the reduction in size. In some designs, differential speed is maintained to exert shearing forces on the particles. The roller surface can be smooth or can carry corrugations, breaker bars, or teeth, so as to increase friction and facilitate trapping of particles between the rolls. Toothed-roll crushers can be mounted in pairs, like the smooth-roll crushers, or with only one roll working against a stationary curved breaker plate. Toothed-roll crushers are much more versatile than smooth-roll crushers but have one limitation; they cannot handle very hard solids. They operate by compression, impact, and shear, and not by compression alone, as do smooth-roll crushers. Crushing rolls are widely applied in the milling of wheat and in the refining of chocolate.

Figure 1b shows a *hammer mill*, a piece of equipment containing a high-speed rotor turning inside a cylindrical case. The rotor carries a collar bearing a number of hammers around its periphery. In the rotating action, the hammers swing through a circular path inside the casing containing a toughened breaker plate. Feed passes into the action zone with the hammers driving the material against the breaker plate, forcing it to pass through a bottom mounted screen by gravity when the particles attain a proper size. Reduction is mainly due to impact forces, although under choke feeding conditions, attrition forces can also play a part in such reduction. The hammers may be replaced with knives, or any other device, making possible the mills handling of tough, ductile, or fibrous materials. The hammer mill is a very versatile piece of equipment that gives high reduction ratios and can handle a wide variety of materials from hard and abrasive to fibrous and sticky. In the food industry its applications are quite varied, being extensively used for grinding spices, dried milk, sugar agglomerate, cocoa press cake, tapioca, dry fruits, dry vegetables, and extracted bones.

Disc attrition mills, such as those illustrated in Figures 1c through 1e, use shear forces in size reduction, mainly in the fine size range of particles. There are several basic designs for attrition mills. The single disc mill (Figure 1c) has a high speed rotating grooved disc, leaving a narrow gap with its stationary casing. Intense shearing action results in comminution of the feed. The gap is adjustable, depending on feed size and product requirements. In the double disc mill (Figure 1d), the casing contains two rotating discs that rotate in opposite directions, giving a greater degree of shear compared with the single disc mill. The pin-disc mill carries pins or pegs on the rotating elements. In this case, impact forces also play an important role in particle size reduction. The Buhr mill (Figure 1e), which is an older type of attrition mill, originally used in flour milling, consists of two circular stones mounted on a vertical axis. The upper stone is normally fixed and has a feed entry port, while the lower stone rotates. The product is discharged over the edge of the lower stone. The applications of attrition mills in the food industry are quite extensive. They have been employed in dry milling of wheat, as well as wet milling of corn for the separation of starch gluten from the hulls. Other applications include breaking of cocoa kernels, preparation of cocoa powder, degermination of corn, production of fishmeal, manufacture of chocolate, and grinding of sugar, nutmeg, cloves, roasted nuts, peppers, etc.

A *tumbling mill* is used in many industries for fine grinding. It basically consists of a horizontal, slow speed, rotating cylinder that is partially filled with either balls or rods. The cylinder shell is usually made of steel, lined with carbon-steel plate, porcelain, silica rock, or rubber. The balls are normally made out of steel or flint stones, while the rods are usually manufactured with high carbon steel. The reduction mechanism is carried out as follows: as the cylinder rotates, the grinding medium is lifted up the sides of the cylinder and dropped onto the material being comminuted, filling the void spaces between the medium. The grinding medium components also tumble over each other, exerting a shearing action on the feed material. This combination of impact and shearing forces brings about a very effective size reduction. As a tumbling mill basically operates in a batch manner, different designs have been developed to make the process continuous. In a tube mill, the cylinder has a slope with a horizontal plane; thus, the material travels a single pass while being reduced. 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, achieving thus a segregation of grinding media with a consequent rationalization of energy. An efficient way to segregate the grinding medium is to use the conical ball mill illustrated in Figure 1f. While the feed solid enters from the left into the primary grinding zone, where the shell is at maximum diameter, the comminuted product exits through the cone at the right end where the shell is at minimum diameter. As the shell rotates, the large balls move toward the point of maximum diameter, and the small balls migrate toward the discharge outlet. Therefore, the initial breakage of feed particles is performed via the largest balls dropping the greatest distance, whereas the final reduction of small particles occurs with the small balls dropping a smaller distance. In such an arrangement, the efficiency of the milling operation is greatly increased. Among applications of tumbling mills in the food industry, the reduction of fluid cocoa mass can be named.

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Biographical Sketch

Enrique Ortega-Rivas is a Professor at the University of Chihuahua, Mexico. He holds the status of "National Researcher", which is the maximum recognition conferred by the Mexican government to academics based on professional merits and achievements. Dr. Ortega-Rivas also has been recently listed in "Who's Who in Science and Engineering". His research interests include food engineering, powder and particle technology, solid-liquid separation techniques, and fruit processing. Dr. Ortega-Rivas has participated in national and international academic assignments, such as organizing professional meetings, serving on panels, and representing his institution in diverse committees. Dr. Ortega-Rivas has published numerous technical papers in refereed journals and chapters in technical books. He also is a reviewer of manuscripts for different international journals.