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Food Particle Technology. Part II: Some Specific Cases

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ABSTRACT

In Part II the flowability of instant powders for vending machines, the recovery and enrichment of protein from food wastes, and the selective comminution of vegetable foods for protein enrichment serve as practical examples. The relevance to each case of the fundamentals reviewed in Part I illuminates connections which remain obscure when empirical methods, still widely used in food technology, are employed.

1. FLOWABILITY OF INSTANT POWDERS FOR VENDING MACHINES

Many food powders such as instant coffee, dried milk, sugar, cocoa and soup mix are produced specially for use in vending machines. There, the powder is stored in containers from which small portions are metered as required, dispersed or dissolved in (usually hot) water and dispensed as a ready-to-drink beverage or soup into a drinking cup. The powder must possess satisfactory 'instant' properties and also have a good flowability to ensure discharge without flow problems and in the proper quantity. Flow problems with the powder occasionally lead to beverages or soups made with insufficient dry matter. This may be due to inadequate design of the feeder or of the storage container, or to inadequate flowability of the powder, or both. According to the author's observations, vending machines with inadequate feeders are frequently to be found. These faults in design could be avoided if the guidelines established in the relevant literature (Jenike, 1970; Schwedes, 1970) were followed. But even with properly designed feeders, discharge problems may still occur,

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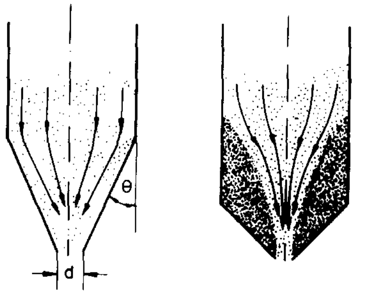

Fig. 1. Mass flow and plug flow from bins.

if the storage container has been designed incorrectly. The cone angle θ (see Fig. 1(a)) is usually small enough to guarantee mass flow, but the outlet opening must be sufficiently large. If the equivalent critical diameter

$$d_c^* = \frac{d_c}{H(\theta)} \tag{1}$$

of the outlet is introduced, it follows from eqn (1) (see eqn (21), Part I)

$$d_c = \frac{\sigma'_{1c} H(\theta)}{\rho_b g} \tag{2}$$

(where ρ_b is bulk density, g is acceleration due to gravity, σ'_{1c} is critical stress and $H(\theta)$ is a function of the geometry of the hopper given by published diagrams (Jenike, 1970)) that

$$\sigma'_{1c} = d_c^* \rho_b g \tag{3}$$

To make sure that the bin is also suitable for bulk material of poor flowability, σ'_{1c} and hence d_c^* must be as large as possible. In the majority of cases the maximum value of d_c is about 20 mm, since only small quantities are to be dosed. It is recognized from eqn (1) that $H(\theta)$ should be a minimum for large d_c^* values. According to the diagrams of Jenike, the smallest values for $H(\theta)$ are obtained for long, rectangular hoppers with a small cone angle θ.

Producers of instant food powders for vending machines have difficult demands to meet since the material should be suitable for any type of vending machine in use. Equation (3) shows first that a high bulk density ρ_b is desirable. It is possible, by selecting adequate processing conditions during instantizing, to produce agglomerates with low porosity and consequently high bulk density; however, the instant properties suffer diminution so that a compromise is necessary. Unfortunately the bulk density of food powders intended for vending machines is often fixed as the quantities have to be metered volumetrically.

It is therefore important both to instantize the food powder adequately and to ensure that it is sufficiently flowable for use in vending machines. The diagram in Fig. 3 is a development of Fig. 2. For the usual vending machines, the σ_1' straight lines for the bulk material in question must first be determined according to eqn (4) (see eqn (20), Part I)

$$\sigma_1' = \frac{\sigma_1}{ff} = \frac{\sigma_1}{f(\theta, \phi_e, \phi_w)} \tag{4}$$

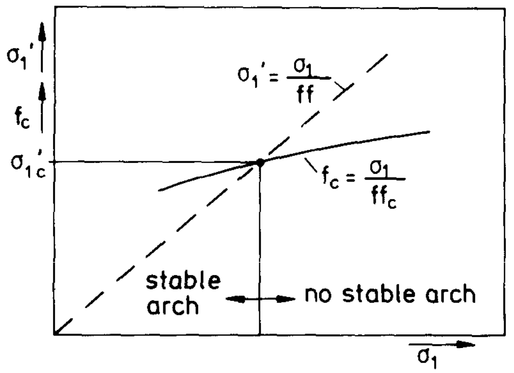

Fig. 2. Graphical construction to determine the critical diameter of a bin outlet (for explanation see text).

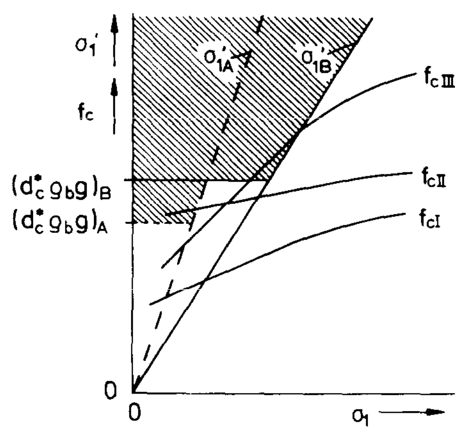

Fig. 3. Graphical construction to determine the adequacy of flowability of powders for use in vending machines.

where σ_1' is the major principal stress acting at the abutment of an arch, σ_1 is the principal stress, *ff* is the flow factor, ϕ_e is the effective friction angle and ϕ_w is the friction angle between bulk material and wall.

For two vending-machine bins, A and B, these straight lines σ_{1A}' and σ_{1B}' as well as the appropriate critical pressures which act at an abutment, $\sigma_1' = d_c^* \rho_b g$ are plotted (eqn (3)). Particulate material will flow only if the unconfined yield strength, f_c, does not enter the hatched area. This may be illustrated by the f_c curves of three different powders I, II and III shown in Fig. 3. If the powders tend to consolidate with time, the f_c values should be those after consolidation for 60 h. Such a period allows for the time during which the vending machines might not be used over weekends. Powder I would be discharged satisfactorily from either bin, since the f_{cI} curve does not intersect either hatched area. Powder II would be discharged satisfactorily from bin B, but not from bin A, and *vice versa* for powder III. Such flow behaviour, often regarded as mysterious, is easily explained by Fig. 3.

To establish a diagram such as Fig. 3 for a particular machine, not only the specific characteristics of the hopper, but also the yield loci for the individual powders must be determined experimentally. An example is shown in Fig. 4. The material, batch II of an instant cocoa mix (main components: 80% sugar, 20% cocoa), was produced batchwise in an industrial fluidized bed instantizer. For the different consolidation

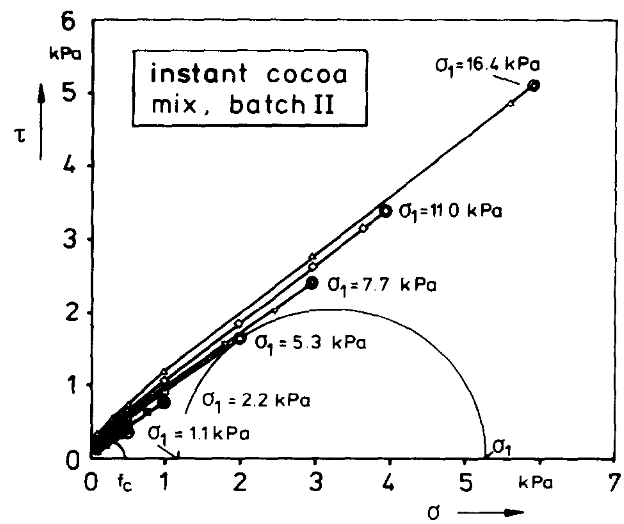

Fig. 4. Yield loci of an instant cocoa mix (batch II) (as measured by the annular shear tester of Fig. 11(b) in Schubert, 1986).

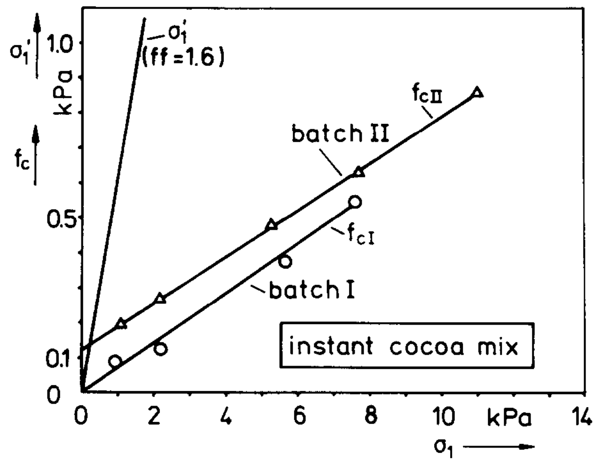

Fig. 5. Linearized unconfined yield strength f_c and $\sigma_1' = \sigma_1/ff$ as a function of the major consolidation stress σ_1 for two batches of an instant cocoa mix.

conditions the major consolidation stresses σ_1 for each yield locus are given. For the yield locus with $\sigma_1 = 5{\cdot}3$ kPa the Mohr semi-circles have been drawn to determine σ_1 and f_c. The yield loci were measured by using the annular shear cell as modified by Ehlermann (see Rüger, 1982). Consolidation with time was not found.

An evaluation of the results according to Fig. 2 leads to the graph shown in Fig. 5. The figure shows the f_c curve of batch II (f_{cII}) as determined from Fig. 4 and also the f_c curve of a different batch of the same instant cocoa mix (f_{cI}). According to Molerus (1982), the f_c values, as a function of σ_1, may be represented as straight lines; this also corresponds well with the measured points which were evaluated according to Jenike (1970). Figure 5 demonstrates the necessity of linearizing the f_c curves, since otherwise the required point of intersection with the σ_1' straight line could not be extrapolated reliably. However, the example underlines also the necessity of measuring shear-forces at extremely small normal stresses, since otherwise it is impossible to determine the point of intersection between the f_c curve and σ_1' straight line with sufficient accuracy. The example illustrates furthermore the differences in flowability of nominally the same food powder arising in practice from fluctuations in processing. Batch I has ideal flow properties for a bin, since the f_c curve passes through the origin. The flow function is independent of σ_1' and has the value of $ff_c = \sigma_1/f_c = 14$; according to Table 1, batch I is therefore non-cohesive and free-flowing. Batch II, however, reacts differently; at the point of intersection between the f_c and σ_1' lines,

TABLE 1
Flowability of Powders, Classified According to the Jenike Flow Function $ff_c = \sigma_1/f_c$

$ff_c < 2$	Very cohesive, non-flowing	Cohesive powders
$2 < ff_c < 4$	Cohesive	
$4 < ff_c < 10$	Easy-flowing	Non-cohesive powders
$10 < ff_c$	Free-flowing	

which determines the flowability at the bin outlet, $ff_c = 2$, which, according to Table 1, indicates a cohesive powder. Batch II was indeed found not suitable for use in vending machines and had to be withdrawn from the market. This example demonstrates the use of appropriate shear-force measurements for both production control and product development. Such measurements are also helpful in determining quantitatively the effect of flow conditioners to improve the flowability of powders. In the present case, measurements showed that the addition of 0·1% amorphous silicon oxide (Aerosil) would have been sufficient to render batch II suitable for vending machines. In the Federal Republic of Germany, however, the use of flow conditioners for instant cocoa mixes is illegal. Here, only the flow behaviour in the hopper has been discussed. Difficulties may also arise from incorrectly designed feeders.

2. PROTEIN ENRICHMENT FROM FOOD WASTES

During food processing, residues are frequently obtained in large quantities which may still contain valuable substances. Particle technology has been used to investigate the enrichment of such valuable ingredients from food waste with the objective of using them for human consumption.

Hoffmann *et al.* (1980), for example, studied at the author's institute the recovery of protein from brewers' spent grain by mechanical processing. Spent grain is a by-product of breweries which is at present used mainly as fertilizer or animal feed or disposed of as waste. The spent grain contains about 20% dry matter; the rest is water. About 24–28% of the dry matter consists of protein which has been denatured by heat during the brewing process and which therefore cannot be recovered by physico-chemical means such as dissolution in water and subsequent precipitation. The main solid components of the spent grain besides water, are husks, germ and a doughy mass. Whereas the protein content of the husks is only about 7%, the remainder may contain more than 50% protein. For protein enrichment, the coarse-sized husks have to be separated from the fines which adhere strongly to them. This is accomplished by dispersion of the entire material to overcome the adhesion forces, and subsequent or simultaneous separation of the protein-rich fraction from the husks. Hoffmann *et al.* investigated the following processes.

(a) Dry process

In the dry process, the entire spent grain is dried and comminuted dry; subsequently the fines enriched with protein are separated from the coarse-sized husks by sieving and/or air classification. As mentioned previously, however, interparticle adhesion in a gaseous environment is about one order of magnitude stronger than in aqueous suspension. The dry material must therefore be ground in such a way that some of the husks are also comminuted and enter the fines fraction. The protein enrichment achieved by this method was therefore only 35–40% crude protein as a maximum. By optimization of grinding and separating processes protein enrichment up to about 48% is possible (Finley and Hanamoto, 1980). However, since the entire initial material must be dried first, this process is uneconomical and was not pursued further.

(b) Wet process

Here the initial material is suspended in additional water and dispersed in the liquid by shear forces produced by special stirring equipment. Subsequently the husk-rich (i.e. low-protein) fraction is separated from the remaining material by sedimentation and/or sieving. Due to the weaker interparticle adhesion in water a protein enrichment of up to 65% may be achieved. In this case the husk fraction is practically free from any adhering protein-containing material (Loncin and Schornick, 1977). A disadvantage of the method is the high water consumption and consequent need for waste-water treatment which increase the costs of the entire process considerably. Another cost factor is dewatering of the fractions. These economic aspects limit the applicability of the process in practice.

(c) Direct process

In this case, the moist spent grain, without addition or removal of water is sheared to overcome interparticle adhesion and separated in one operation into a husk-rich dewatered fraction and protein-rich wet

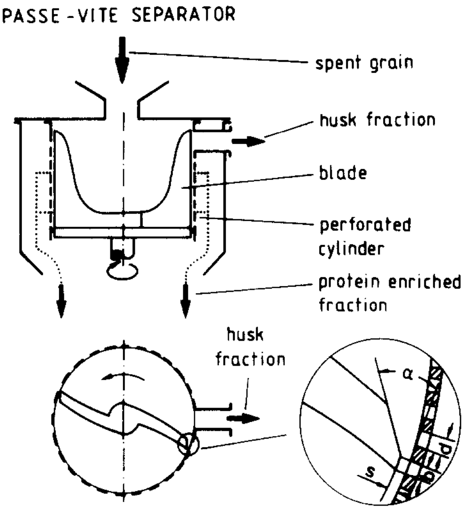

Fig. 6. Sectional view of the 'passe-vite' separator optimized for protein enrichment from brewers' spent grain.

material. This may be accomplished in screw presses with a peripheral separating sieve (Hoffmann *et al.*, 1980). Since screw presses demand high maintenance and tend to block, Hoffmann developed the passe-vite separator, Fig. 6; the apparatus works on the same principle but has fewer problems in its operation and allows a greater throughput. The principle of separation into husk-rich and protein-rich fractions is shown in the diagram. The apparatus is a commercially available separator which has been modified for this specific task. For this purpose Hoffmann optimized the blade geometry, i.e. the approach angle α, the clearance s, the blade tip thickness b and the perforation diameter d, as shown in Fig. 6, in such a way that maximum protein enrichment is achieved as a function of the yield. The separating principle is as follows: the moist spent grain is compressed between blade and perforated cylinder to such an extent that excess water is obtained, i.e. that the liquid saturation $S = 1$ is exceeded. Thus capillary forces are excluded (see Fig. 7); only the much smaller adhesion forces of the particles suspended in the liquid must be overcome by shearing. The protein-rich fines are pressed through the sieve holes, whilst the fibrous husks remain inside due to their preferred orientation parallel to the cylinder wall, which prevents them from passing through the sieve holes. Pilot experiments have shown that this method can produce concentrates containing more than 60% protein, dry basis. The enrichment is accompanied by a change in water content. The compression stage reduces the water

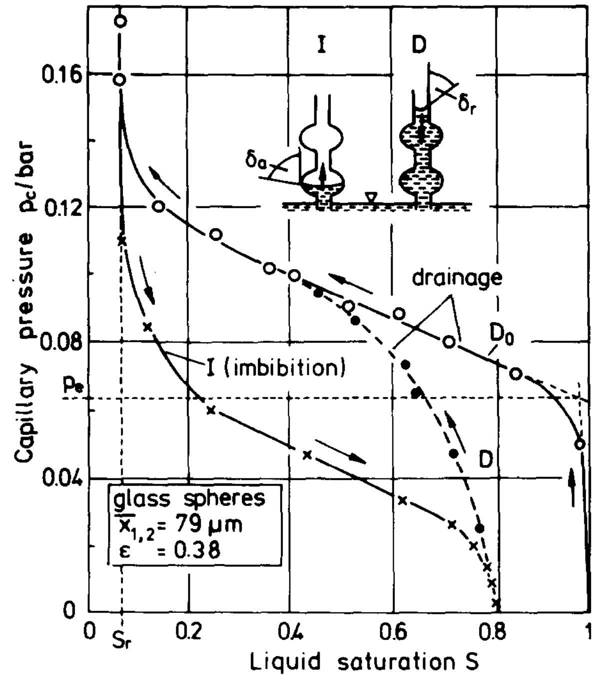

Fig. 7. Capillary pressure of a bulk material (glass spheres, weighted mean diameter $\bar{x}_{1,2} = 79$ μm, porosity $\varepsilon = 0{\cdot}38$) *vs.* degree of liquid saturation ($p_c(S)$ = capillary pressure curve).

content of the husk fraction to about 65% and increases that of the protein concentrate to about 87%, as compared to about 80% water content of the original spent grain. To facilitate further processing, the protein concentrate is then dewatered as much as possible mechanically, dried, and finally ground to the desired degree of fineness. The dewatered husk fraction obtained as a by-product may be used direct for cattle feed. Drying is necessary only for the protein enriched fraction.

As in any enrichment process, the desired substance content varies inversely with yield. For the evaluation or comparison of processes it is essential to know the desired substance content as a function of yield. Figure 8 shows for the present example the protein content c_p of the fines fraction *vs.* the yield Y for the different processes. Yield is defined here as a mass of dry protein concentrate over the mass of dry initial spent grain. The chain-dotted line c_{po} indicates the protein content of the initial spent grain; the dashed curve c_{pideal} indicates the theoretical maximum protein content for different yields, on the assumption that the entire protein is contained in the enriched fraction. This ideal condition

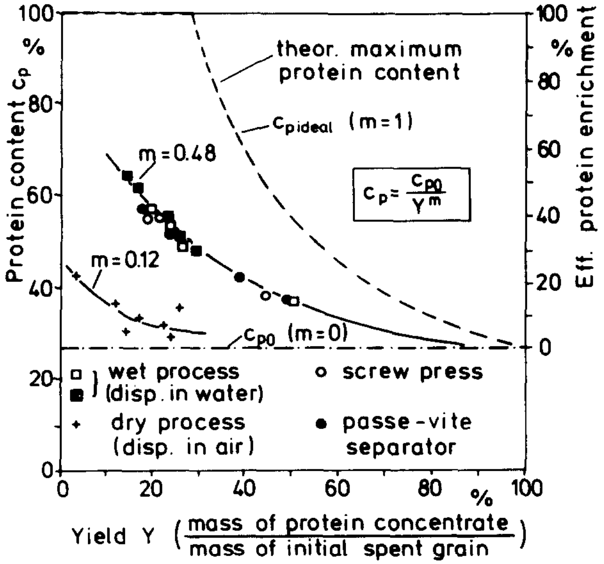

Fig. 8. Mean protein content c_p *vs.* yield Y of concentrate obtained from brewers' spent grain by different enrichment processes.

cannot be fulfilled by merely mechanical processes, since the proteins originally contained in the husks always remain in the low-protein fraction. The values attainable in practice are in the range confined by the curves c_{po} and c_{pideal} and may in the present case be approximated by the equation

$$c_p = \frac{c_{po}}{Y^m} \tag{5}$$

which is valid for $Y \geq (c_{po})^{1/m}$, where Y is yield. Factor m which has to be determined experimentally may be regarded as a value characterizing the degree of protein enrichment. Exponent $m = 1$ applies to the ideal curve c_{pideal}, whereas $m = 0$ applies to the curve $c_{po} = 0{\cdot}27$ where no enrichment takes place. The experimental points show that the dry process leads to the lowest enrichment for a given yield ($m \simeq 0{\cdot}1$), whereas all the remaining processes show approximately the same protein enrichment as a function of yield with a value of $m = 0{\cdot}48$. Preference should consequently be given to the simplest and most economical process, i.e. the passe-vite separation. The graph shown in Fig. 8 provides the basis for assessing and comparing different separators and also indicates practical yield attainable for a given protein content. If, for instance, a fraction of 40% protein content is required, the yield is about 45%; a 50% protein concentrate is attainable with a yield of about 28%.

The protein concentrate from spent grain has been shown to be suitable for many applications such as including it in bread, confectionery and extrusion products. The dried and comminuted concentrate, a yellow-brownish powder, has a pleasant odour of freshly ground barley and presents no processing problems. Its protein quality, due to the amino-acid composition, is similar to that of the majority of cereals; its nutritional value and protein digestibility are comparable to those of coarse wheat flours.

Worldwide, about 13 million tons of brewers' moist spent grain are available yearly with a solid content of about 2·6 million tons of which about 0·68 million tons are crude protein, enough to produce, according to the yield curve in Fig. 8, 190 000 tons concentrate of 50% protein, i.e. 95 000 tons crude protein. Even if this quantity is very small compared to the soya protein produced worldwide, it should still be considered for human nutrition in view of its simple and relatively low cost of recovery. This is particularly the case where brewers' spent grain is disposed of as waste at additional cost.

3. SELECTIVE COMMINUTION OF VEGETABLE FOODS

The principle underlying these processes is very old and has been used by conventional cereal grain milling for a long time. By comminution of the grains, different components of the material, depending on the particle size, are obtained since — as mentioned before — homogeneity of a particulate material generally increases with decreasing particle size. If the ground product is separated into coarse and fine fractions, each contain different components. All these processes are based on the fact that the different components are not equally distributed on a microscale in the original food, so that here the grain components which are more easily grindable will be enriched in the fines. A product also may be comminuted in such a way that fractures occur predominantly at the interfaces between components; in this case the individual, largely unbroken components are released as separate particles. Both cases in which the liberation of components is effected by the use of only mechanical forces is referred to as selective comminution.

By separation according to different particle characteristics such as size and density, fractions with different proportions of components are obtained if the differential characteristic corresponds to one of the components. Selective comminution and subsequent separation must therefore be considered together in assessing the success or failure of separation of ingredients into individual fractions. Dry processes are usually preferred in cases where the material is not initially wet, to save the costs of drying and to avoid consequent damage to the product by heat.

Numerous publications were evaluated by Heideker and Hoffman (1986) in a review paper dealing with the displacement of food components by selective comminution and separation mainly by air classification. In a review paper Vose (1978) discussed the principles, applications and practical implications of protein displacement in vegetable foods by means of air classification. Studies so far have mainly concerned cereals (see Wu and Stringfellow, 1979), legumes (see Reichert, 1982), dried potatoes (see Holm, 1980) and oilseeds (see Kadan *et al.*, 1980), as well as the yield and functional properties of air-classified protein and starch fractions of different flours of vegetable origin (Sosulki and Youngs, 1979). Experience has shown that milling processes usually lead to protein enrichment in the fines. Thus points to the conclusion that protein has better comminuting properties than other components. Figure 9 shows the cellular structure of cereals (wheat) and

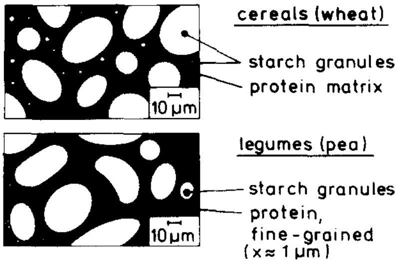

Fig. 9. Diagram of the characteristic cellular structure of cereals (wheat) and legumes (pea).

legumes (peas) by way of example. Only the two main components, starch and protein, are shown in a simplified way. Protein forms the matrix in which the starch granules are embedded. In the case of wheat, the protein forms a continuous matrix, whereas the matrix of legumes consists of fine protein grains of about 1 μm in size. The starch granules of legumes are about one order of magnitude larger than the protein particles. In wheat, the protein matrix contains both, small spherical starch granules (diameter $x = 1$–10 μm) and large lenticular starch granules ($x = 15$–40 μm and more) occur.

If high-protein fines are required, it is necessary to disintegrate the protein matrix by a selective grinding process; the large starch granules are to remain intact and are only isolated by the grinding process. Figure 9 shows that selective fine-milling of the protein matrix of legumes, due to the fine-grained structure, is less difficult than that of wheat. The wheat protein matrix, furthermore, still contains very fine starch granules which are isolated only at very high comminution levels; these granules then join to the fines from which they are difficult to separate. Such fine grinding also damages the large starch granules. Fine fragments of these starch particles join the fines and thus reduce the protein displacement. Damaged starch granules also affect the baking quality of flour. Thus, the attainable degree of protein displacement, s_p, depends not only on the selective comminution and subsequent air classification, but also on the nature of the food material itself. The value of s_p varies from about 5% in conventionally milled hard wheat flours to about 45% for impact-milled legume flours. The degree of protein displacement is given by (see also Vose, 1978)

$$s_p = \frac{1}{c_{po}} \sum_{i=1}^{n} (c_{pi} - c_{po}) Y_i \qquad (6)$$

where c_{po} is protein content of the parent flour, c_{pi} is protein content of individual fractions with higher protein level than the parent, Y_i is fractional yield of individual fractions and n is number of fractions produced out of the parent stock.

If the material is separated into two fractions

$$s_p = \frac{c_p - c_{po}}{c_{po}} Y \qquad (6a)$$

where c_p is the protein content of fines and Y the yield of fines; Y is defined in this case as the ratio of the mass of the fines fraction to the total mass of the parent fraction.

The degree of protein displacement according to eqns (6) and (6a) has the advantage of depending in practice only little upon the yield selected in each case. It is therefore possible to characterize the quality of a protein displacement, independent of the yield, approximately by one single numerical value. This is demonstrated, for example, in the protein enrichment of brewers' spent grain discussed above. From eqns (5) and (6a)

$$s_p = Y(Y^{-m} - 1) \qquad (7)$$

On the basis of the experimentally determined exponent $m = 0{\cdot}48$ for the wet and direct processes, the following values are obtained:

Y:	0·5	0·4	0·3	0·26	0·2	0·1
s_p:	0·20	0·22	0·23	0·24	0·23	0·20

In the present example, the optimum degree of protein displacement is $s_{\text{popt}} = 0{\cdot}24$ in a yield $Y_{\text{opt}} = 0{\cdot}26$. These values are obtained from eqn (7) under the condition of $\mathrm{d}s_p/\mathrm{d}Y = 0$

$$s_{\text{popt}} = m(1-m)^{(1-m)/m} \tag{8}$$

$$Y_{\text{opt}} = (1-m)^{1/m} \tag{9}$$

It should be noted that eqns (7)–(9) as well as eqn (5) are valid only in the range $Y \geqq c_p^{1/m}$.

A disadvantage of the displacement degree given by eqn (6) as found in the literature is the fact that the value in question is not standardized. It can be derived from the mass balance that $s_p \leqq 1 - c_{po}$ is always valid, i.e. the maximum value

$$s_{\text{pmax}} = 1 - c_{po} \tag{10}$$

cannot be exceeded. By using eqn (10) the standardized degree of protein displacement may be defined from eqn (6)

$$s_p^* = \frac{s_p}{s_{\text{pmax}}} = \frac{1}{c_{po}(1-c_{po})} \sum_{i=1}^{n} (c_{pi} - c_{po}) Y_i \tag{11}$$

which may range between 0 and 1, or 0 and 100%. It is therefore reasonable to call s_p^* the efficiency of protein displacement. However, $s_p^* = 1$ is realized only for the total yield

$$Y = \sum_{i=1}^{n} Y_i = c_{po}$$

for all remaining Y values: $s_p^* < 1$. A characteristic value which is always between 0 and 1 for all yields is the efficiency of protein enrichment

$$\eta_p = \frac{c_p - c_{po}}{c_{\text{p ideal}} - c_{po}} \tag{12}$$

where $c_{\text{p ideal}} = c_{po}/Y$ (see Fig. 8). Using the form of eqn (6)

for $$Y \leqq c_{po}:\ \eta_p = \frac{1}{Y(1-c_{po})} \sum_{i=1}^{n} (c_{pi} - c_{po}) Y_i$$

for $$Y \geqq c_{po}: \eta_p = \frac{1}{c_{po}(1-Y)} \sum_{i=1}^{n} (c_{pi} - c_{po}) Y_i \qquad (13)$$

In the special case of $Y = c_{po}$, $\eta_p = s_p^*$.

The careful definition and selection of appropriate quantitative characteristics to evaluate the displacement of ingredients by selective grinding and subsequent separation — usually by air classification — are a prerequisite for the comparison of different processes and the evaluation of individual process stages. This point is frequently neglected in the literature; hence many results cannot be adequately evaluated or compared with other results published (Heideker and Hoffmann, 1987). The fact that it is still impossible to decide precisely what comminution conditions are most suitable for optimizing selectivity was the reason for this present study of the problem.

Selective comminution is used industrially to isolate individual components, comparable to the liberation of minerals in ore beneficiation. This requires that the components to be separated, have different particle sizes to enable them to be separated, say, by air classification. Recent advances in fracture mechanics and particle breakage are invaluable to this work. In view of the complexity of processes taking place during particle breakage (Schönert, 1981), however, only brief reference may be made here. The size reduction of particles is effected primarily by impact or compression forces and occasionally by shear forces. The deformation rate in particles subjected to impact as, for instance, in pin mills, is substantially higher than in particles compressed, say, in roller mills. In the case of materials with elastic or plastic properties, however, the deformation rate has scarcely any influence on particle breakage, in contrast to viscous substances in which higher deformation rates improve size reduction (Schönert, 1981) since their deformation is dependent upon time. Common to all materials, as has been mentioned before, is an increase in strength with decreasing particle size. In the case of brittle substances the resistance to breakage of a particle of $x = 5$ μm in size is about 100 times greater than of a particle of $x = 100$ μm. Any substance loses its brittleness when the particle size is sufficiently small.

The behaviour of individual components of dried food unfortunately has not been extensively explored. However, it is probable that, depending on the residual water content, these materials may exhibit in suitable circumstances elastic, plastic and viscous behaviour. It is essential for selective comminution that the individual components respond differently to the grinding process.

The result of selective comminution can be judged only after separation of particles. In view of the required fineness of particles, separation according to particle size by air classifiers is the method of choice in the majority of cases. A strict classification at a given cut point x_{cp} ensuring that all particles of the size $x < x_{cp}$ pass into the fines and all particles of $x > x_{cp}$ into the coarse material would be ideal, but a perfect classifier does not exist. A real classification is evaluated by the grade efficiency

$$T(x) = \frac{bq_b(x)}{q_a(x)} = 1 - \frac{fq_f(x)}{q_a(x)} \tag{14}$$

where b is the mass of coarse material as a fraction of the mass of initial material, f is the proportion of fines, and $q_a(x)$, $q_b(x)$ or $q_f(x)$ are the frequency distribution of the feed material (a), coarse material (b) and fines (f). In the above example of protein enrichment in the fines, the proportion of fines, in the case of a single classification, is identical to the yield (protein yield). The grade efficiency $T(x)$ indicates, for any particle size x, the mass fraction of feed material appearing in the coarse fraction. Plotting the grade efficiency $T(x)$ *vs.* the particle size x yields the so-called grade efficiency curve. An example is shown in Fig. 10. The cut point x_{cp} is at $T = 0{\cdot}5$, indicating the size of particles half of which appear in the coarse material and half in the fines. The graph further shows the particle sizes $x_{25,t}$ and $x_{75,t}$ and, as a dashed line, the ideal grade efficiency curve with an absolutely sharp classification at x_{cp} which is not attainable in reality. The value $\kappa = x_{25,t}/x_{75,t}$ is used to characterize the sharpness of cut, $\kappa = 1$ being ideal classification. The best industrial air classifiers achieve $\kappa = 0{\cdot}7$, many commercial classifiers show κ values of 0·3–0·6. Agglomeration of fines prior to or during classification, due to

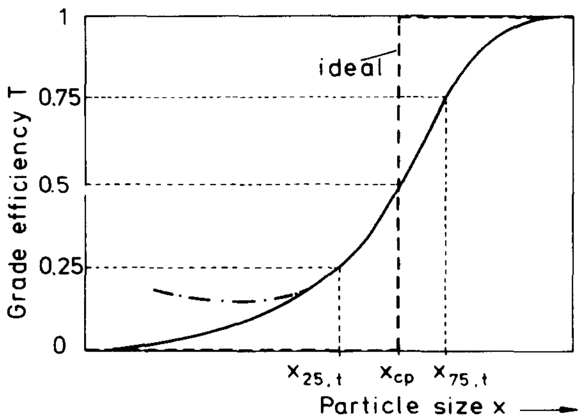

Fig. 10. Real and ideal grade efficiency curves.

interparticle adhesion, represents a special problem. In this way more fines pass into the coarse fraction; this may considerably reduce the degree of protein displacement. A grade-efficiency curve reflecting a state in which fine particles are agglomerated is shown in Fig. 10 by the chain-dotted curve. A comprehensive survey of classification of particulate solids in air classifiers and their design is provided by Leschonski (1977).

The combined effect of selective size reduction and air classification in displacing components can also be determined quantitatively. Figure 11 shows, for example, the protein displacement by a single classification into fine and coarse fractions of the selectively ground product. The left diagram shows the protein content c_{px} as a function of the particle size x after grinding. It would be ideal if all the protein were in the fines $x < x_{cp}$ ($c_{px} = 1$), and none ($c_{px} = 0$) in the coarse material $x > x_{cp}$. Ideal classification would then result in the ideal outcome with the mean protein content c_p as a function of the proportion of fines f, as is shown in the diagram on the right of Fig. 11. Ideal classifications with the cut point $x \leqq x_{cp}$ always produce the value of $c_p = 1$. Since only one cut is made, the fraction of fines f is equal to the yield Y. If, despite ideal selective grinding, a real grade efficiency curve is assumed for the classification, the chain-dotted curve is obtained. In reality, however, this curve is not attainable either, since real milling (see Fig. 11, left) does not produce particles consisting either exclusively of or completely free from protein. The real mean protein content c_p in the fines can be calculated as a

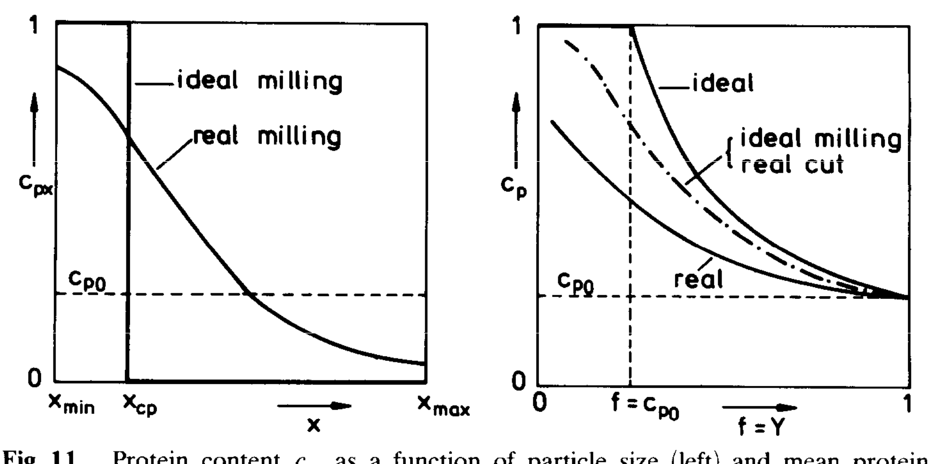

Fig. 11. Protein content c_{px} as a function of particle size (left) and mean protein content c_p as a function of yield Y (right) for real and ideal milling and classification conditions.

function of the yield $Y=f$:

$$c_p = \int_0^\infty c_{px}(x) q_{3f}(x)\,dx \tag{15}$$

where $q_{3f}(x)$ is the frequency distribution by mass of the fines fraction. From eqn (14)

$$c_p = \frac{1}{f}\int_0^\infty c_p(x)[1 - T(x)] q_{3a}(x)\,dx \tag{16}$$

where q_{3a} is the frequency distribution by mass fraction of the ground material entering the air classifier. Equation (16) thus provides the desired relation between c_p and f and shows in which way grade efficiency $T(x)$, protein content $c_{px}(x)$ of the particles and the particle-size distribution $q_{3a}(x)$ of the selectivity ground material influence the result. Using eqn (16), protein displacements can be computer-simulated and optimized in relation to real grinding and classifying processes; in doing so, an extension of eqn (16) to several separation cuts (not shown here) may be necessary.

In Fig. 12 experimental results obtained by Heideker concerning protein displacement in pea flour is presented. The mean protein content

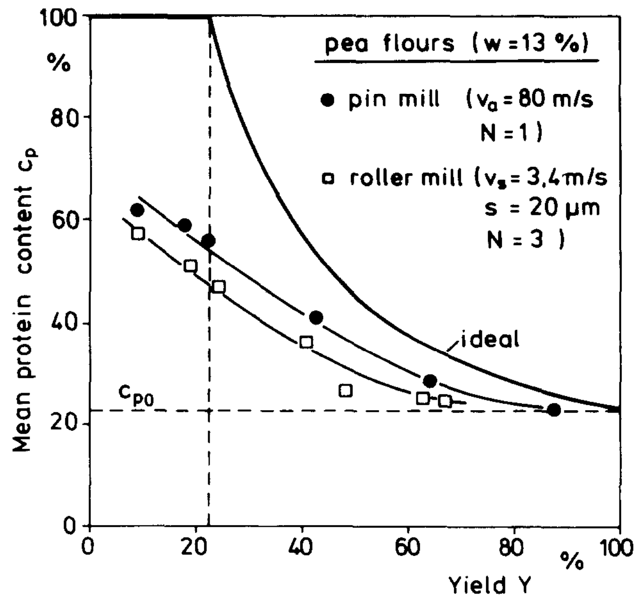

Fig. 12. Mean protein content *vs.* yield of pea flours produced by two different methods of selective comminution.

c_p of the fines after several separation cuts using a spiral air classifier is plotted against the yield $Y=f$. The pea flour, initial protein content $c_{po}=23\%$, water content $w=13\%$, was comminuted either once $(N=1)$ in a pin mill (peripheral speed $v=80$ m s^{-1}) or three times consecutively in a roller mill (peripheral speed $v_s=3{\cdot}4$ m s^{-1}, gap width $s=0{\cdot}20$ μm). For comparison, the ideal protein displacement curve has also been plotted. The more efficient protein displacement is by impact milling. With $Y=23\%$ the standardized protein displacement degree is $s_p^*=\eta_p=0{\cdot}42$ in the case of the pin mill and $s_p^*=\eta_p=0{\cdot}31$ in the case of the roller mill. This result is primarily due to greater fineness of the material after impact milling; a definite judgement of the selectivity of both comminuting processes hence is not yet possible.

Protein enrichment with pea and other grain/legume flours may influence specific product properties such as crispness of bread, rolls and cakes. Protein-enriched flours, however, are of particular interest as substitutes for soya protein, especially to those countries which are dependent upon imported soybean products. The coarse fraction from the classifier, i.e. the starch concentrate, has also been marketed successfully. The residual protein content of about 5% may, if necessary, be removed by wet processing. Air-classified starchy flours are used by industry, for example, to produce special adhesives, or for microcapsule coating (Vose, 1978).

Summarizing, the displacement of food components by selective size reduction and air classification is already in use today and will be increasingly used in future to manufacture new products, to improve quality and especially to compensate for seasonal, climatic, variety-dependent and regional quality fluctuations of crop. This last-mentioned will gain in importance as food processing demands more constant quality of raw materials. Other new applications of particle technology are conceivable such as systematic displacement of aroma compounds, vitamins, enzymes, minerals, and of harmful substances. Selective cold grinding and subsequent classification, a process already used to produce hop concentrates, may in the future attract special interest. With these examples the possibilities provided by the methods and processes of particle technology are commended to food engineers.

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