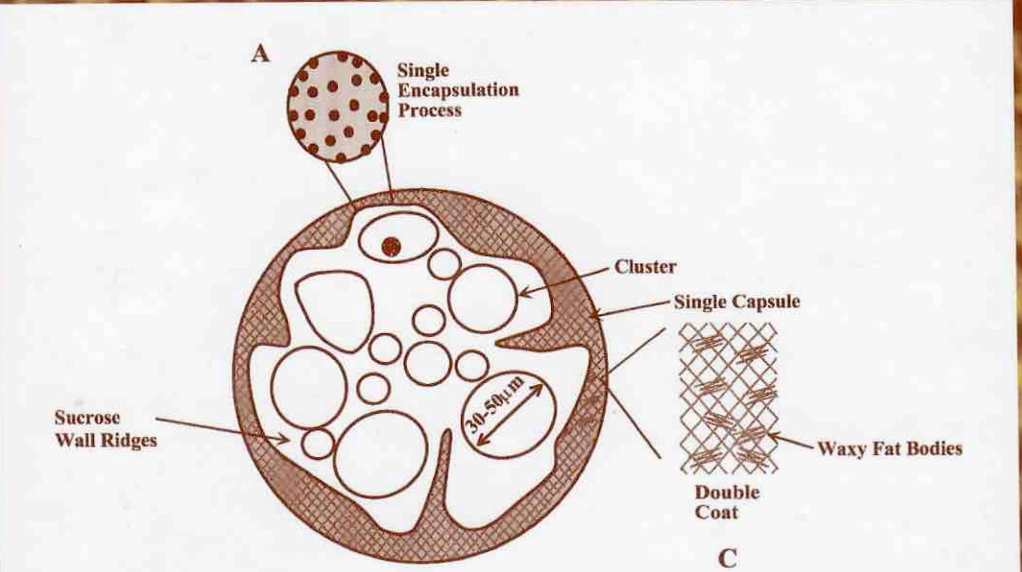
Encapsulated and Powdered Foods



Double Coated Particles

edited by
Charles Onwulata

CRC Taylor & Francis
Taylor & Francis Group

8

Fluid-Bed Coating

E. Teunou and D. Poncelet
Département de Génie des Procédés Alimentaires
École Nationale d'Ingénieurs des Techniques des Industries Agricoles et Alimentaires
Nantes, France

CONTENTS

I. SUMMARY

The chapter presents varied descriptions of the fluid-bed process for coating or air suspension coating, with an emphasis on the Wurster system (the most efficient batch fluid-bed

apparatus), including a discussion on the application and the efficiency of batch fluid-bed systems and their improvement. An analysis of the performance of the batch fluid bed will show that the continuous fluid bed is the economically suitable solution for coating food powders and the schematic of the ideal continuous fluid bed for food powder coating is given as an indication. Phenomena involved in the process of coating fluidized solid particles are studied and some useful techniques to characterize and to evaluate the quality and the efficiency of the process are given and analyzed. Finally, a short classification of the most used coating materials in food and pharmaceutical industries is presented to give a quick view of what can be done with the technique.

II. INTRODUCTION

Fluid-bed coating is one of the various processes that can be employed for encapsulation and coating of food ingredients or additives such as extrusion, solvent extraction, coacervation, cocrystallization, spray drying, mixing and adhesion in rotating drums, etc. [1]. Its specificity is that it allows to really coat dry solid particles (powders), that is, the engulfing of particles into a coating material. This type of coating process leads to capsules called reservoir systems where the particles are surrounded by a layer (Figure 1[a]) or multiple layers (Figure 1[b]) of coating materials.

The ensuing paragraphs are designed to provide some points on the state of this technology, from the description of the process itself to the requirements regarding the powder to be coated, the coating materials, and the characteristics of the resulting products. A review of the various fluid-bed systems will be done here, showing the specificity of each system and the improvement of the coating efficiency. This last point will underline the necessity of the use of the continuous fluid-bed process in food powder coating.

III. GENERAL KNOWLEDGE ON POWDER COATING AND FLUID BED

Every year, tons of food powders are required with some specific properties that the natural product does not offer. The encapsulation of these products provides an alternative to fulfill this request. It is a process where thin films or polymers (coat or shell) are applied to small, solid particles, droplets of liquid, or gases for a variety of aesthetic and protective purposes. Indeed, encapsulation of food powders can separate the reactive components within a mixture, mask undesirable flavors, protect unstable ingredients from degradation factors, such as heat, moisture, air, and light. It can provide controlled or delayed release and reduce hydroscopicity. It also helps in changing the physical characteristics of the original material, for example, flowability and compression improvement, dust reduction, and density modification [2]. In the food industry, enzymes, vegetal proteins, yeast, bacteria, and aroma are encapsulated in maltodextrine or Arabic gum matrix, film coating of extruded products by lipids, resins, polysaccharides, and proteins.

Note that, the emergence of various encapsulation processes is owing to the fact that no encapsulation or coating process developed to date is able to produce the full range of capsules required by different industries. The specificity of the fluid bed is that it leads to real capsules (Figure 1[a] and [b]) compared to spray drying, which leads to a matrix with the core material randomly dispersed in a polymer (Figure 1[c]).

Fluid-bed technology was quite developed during the 1950s, and was applied for various purposes in chemical industries. Its application to particle and powder coating

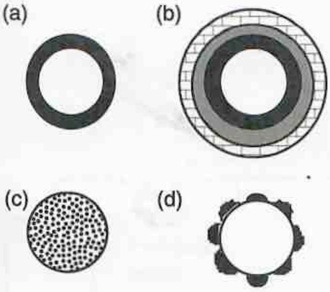


Figure 1 Different types of capsules: (a) reservoir system, (b) reservoir system with multiple layers, (c) matrix system, and (d) imperfect capsule.

Table 1 Comparison of Two Types of Fluid Beds — Batch and Continuous

	Batch (Wurster)	Continuous (horizontal)
Volume (l)	120	120
Flow rate (kg/h)	50	100
Price of the basic equipment in 1999 (€)	1,100,000	610,000
Cost of the coating operation (€/kg)	2.1	0.6
Product quality	Excellent *True reservoir capsules (Figure 1[a] and 1[b]) Uniform batch*	Passable *Presence of capsules with incomplete layer (Figure 1[d]) heterogeneous product*

Notes: Derived from Glatt Pharmatech data. Glatt Pharmatech S.a.r.l., Parc Technologique — rue Louis Neel — 21000 Dijon. With permission.

is relatively recent and was developed to satisfy the growing demand of pharmaceutical, chemical, agrochemical, cosmetic, and food and feed industries. It is still a batch, expensive, and time-consuming process, which is mostly used in pharmaceutical and cosmetic industries that are able to compensate the cost of the process by the high price of their final product. Its application to food powder coating, which is in unfavorable competition with spray drying (a well-established technology), is actually limited to some high value products, because it is well known that one of the imperative goals of the food industry is to offer foodstuff at low prices, for example, despite the high performance of the Wurster system (see later in the chapter), its use in the food industry is problematic because the actual cost of the final coated powder, as it will be seen later (Table 1), is too high. But this tendency is changing as the technology is currently being upgraded to improve its performance, for example, the continuous fluid-bed process, as it can reduce the cost of production and appears to be an attractive alternative for food powder coating.

IV. THEORY OF FLUIDIZATION AND FLUID-BED COATING

A. Fluidization

The principle of fluidization is to maintain particles in suspension in a closed area by blowing air upward through the powder bed resting on a porous gas distributor plate (Figure 2).

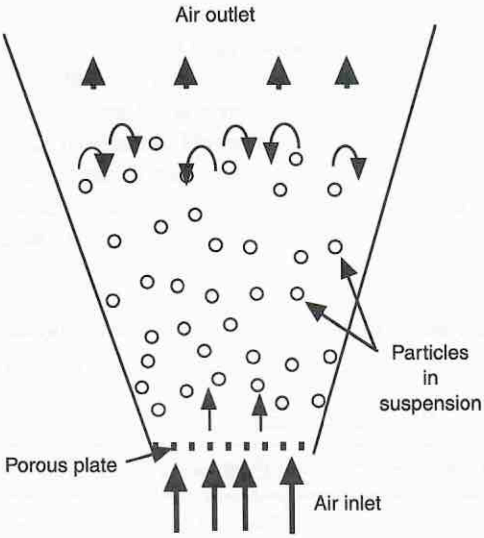


Figure 2 Principle of fluidization.

Many authors [3,4] have described different configurations as a function of air velocity. The state of the fluid bed depends on the air velocity and the powder properties and can be globally described by two equations:

1. The minimum fluidization velocity U_{mf} (Equations [1] and [2]) is given by

$$U_{\mathrm{mf}} = \frac{(\rho_{\mathrm{p}} - \rho_{\mathrm{g}})^{0.934} g^{0.934} d_{\mathrm{p}}^{1.8}}{111\mu^{0.87}\rho_{\mathrm{g}}^{0.066}} \quad \mathrm{d}p < 100\ \mu\mathrm{m} \tag{1}$$

where ρ_{g} is the gas density,
ρ_{p} the particle density,
d_{p} the particle diameter,
d_{v} the diameter of an equivalent sphere, and μ is the gas viscosity.

$$U_{\mathrm{mf}} = \frac{\mu}{\rho_{\mathrm{g}} d_{\mathrm{v}}}\left\{(1135.7 + 0.0408Ar)^{1/2} - 33.7\right\} \quad \mathrm{d}p > 100\ \mu\mathrm{m} \tag{2}$$

where Ar is the Archimedes number $Ar = \rho_{\mathrm{g}} d_{\mathrm{v}}^3(\rho_{\mathrm{p}} - \rho_{\mathrm{g}})g/\mu^2$.

2. The settling or terminal velocity $U_{\mathrm{t}} \cdot U_{\mathrm{mf}}$, that leads to a stable fluid bed (Equation [3]) is given by

$$U_{\mathrm{t}} = \left[\frac{4gd_{\mathrm{p}}(\rho_{\mathrm{p}} - \rho_{\mathrm{g}})}{3\rho_{\mathrm{g}} C_{\mathrm{D}}}\right]^{0.5} \tag{3}$$

where C_{D} is the drag coefficient that is a function of the particle Reynolds number, Re_{p}. A good correlation between C_{D} and Re_{p} for different particle shapes is given in [5].

In short, fluidization, by its principle, appears to be a segregationist system that must be well conducted in order to bring a minimum homogeneity. This homogeneity is the

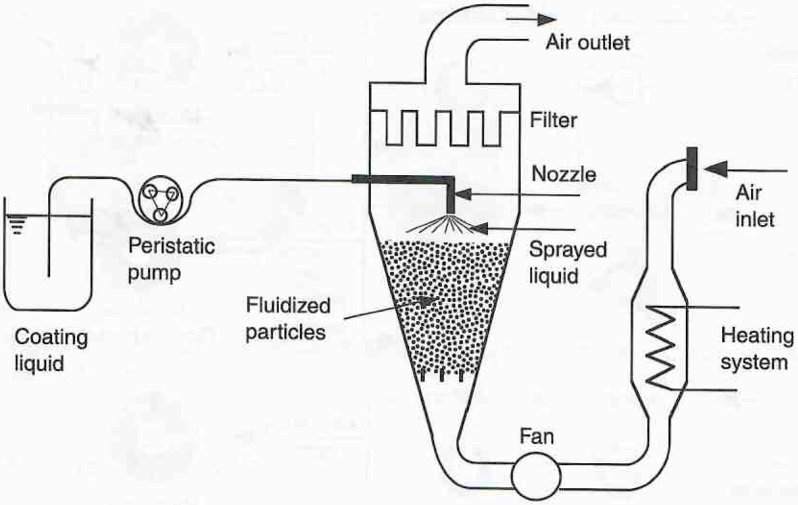


Figure 3 Principle of coating in fluid bed.

real trump that makes this unit operation applicable in various processes such as drying, granulation, agglomeration, pneumatic transport, and of course, coating.

B. Fluid-Bed Coating

The principle of coating in a batch fluid bed is summarized in Figure 3, which presents a top spray coating system: Particles to be coated (the core) whose temperature and flow rate are variable are introduced into the cell and fluidized by an air current. The coating material is pumped to a nozzle through which the material is sprayed on the core, forming a shell.

During this process, what is expected is a homogeneous layering of the coating material on the particles leading to an onion-like structure (Figure 4[a]). Multilayer coating (Figure 4[b]) is achieved by pumping successively different coating materials. Note that the core can be coated by fine particles with the aid of some binders or plasticizers. A raspberry structure (Figure 4[c]) results from this type of coating, which is in fact a granulation process. Note that the agglomeration process is strictly defined as binding of similar particles to give larger agglomerates with a grape structure (Figure 4[d]). This presents the advantages of reducing the fines or dust and consequently enhances the flowability of the resulting granular material.

There are many phenomena during the coating operation because three phases are present: solid (particles), liquid (liquid coating materials), and gas (fluidizing air). These phenomena are classified chronologically here but most of the time many of them take place simultaneously. They are:

1. Air suspension of particles in the coating chamber (particles dynamics).
2. Spraying of coating material as droplets with the objective of increasing the probability of particle-droplets impacts since droplets can easily be dried (heat transfer) before collision with the particle. In this case there is no way for coating to take place.
3. Spreading of droplets on the particle surface followed by flattening and adhesion of the droplet on the particle (mass transfer). Then, in the best case, by the

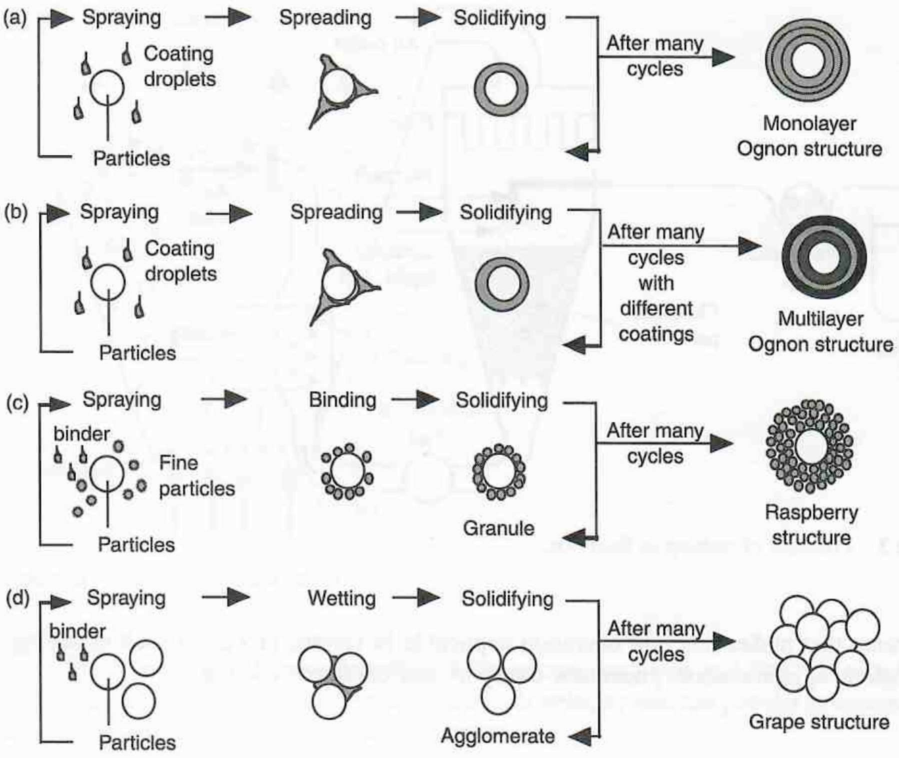


Figure 4 Mechanisms of coating formation and agglomeration in fluid beds. (a) Coating by film layering, (b) coating by film layering multilayer coating, (c) coating by granulation, and (d) as glomeration.

coalescence of droplets on the particle surface before the drying (heat transfer) of the droplets to form a layer.

4. Layering or superposition of different layers of droplets around the particle that results in a homogeneous reservoir system, that is, a real coating. After several cycles of wetting–drying, a continuous film will be formed (Figure 4), with a controlled thickness. It is mainly at this stage that the tendency of agglomeration between two or several particles is high.

Agglomeration is the dreadful phenomenon during the coating process. Indeed, after wetting of the particle surface by the coating material, there is always a competition between continuous layering of the coating material (following the wetting and drying cycle) on the dried particle on the one hand and agglomeration of wetted particles on the other.

The success of the coating operation depends on the spreading of the droplets on the particle surface. This phenomenon is a function of the wettability of particles by droplets and requires a wetting energy [6,7] that depends on the contact angle between the three phases present (solid–liquid–gas) and can be expressed as a wetting coefficient (*Wm*):

$$Wm = \gamma_{\mathrm{sv}} - \gamma_{\mathrm{lv}} - \gamma_{\mathrm{sl}} \tag{4}$$

where γ_{sv} is the interfacial tension between solid and vapor, γ_{sl} the interfacial tension between solid and liquid, and γ_{lv} is the interfacial tension between liquid and vapor.

A liquid can wet a surface if the wetting modulus is larger than zero ($Wm > 0$).

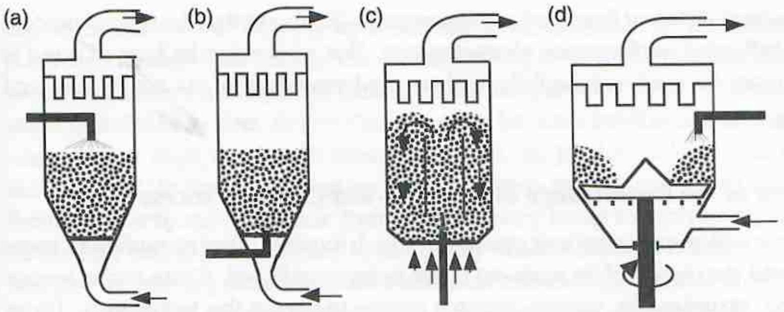


Figure 5 Different types of batch fluid beds: (a) top spray, (b) bottom spray, (c) Wurster, and (d) rotor with side spray.

V. APPLICATIONS

A. Different Types of Fluid-Bed Coaters

1. Top Spray Processing

In the 1950s the coating operation was done in the available top spray granulators (Figure 5[a]), a system where the coating material is sprayed from the top of the product container. Its efficiency in terms of deposited material (spray drying of the coating material) and coating quality (Figure 1[d]) is poor. The resulting capsules present worse controlled release kinetics. So, despite its availability, its big capacity, and the easily accessible sprayer, the top spray is not the one for coating but the system is very useful for agglomeration and granulation.

2. Bottom Spray (Wurster) Processing

This type of processing, where the coating liquid is sprayed from the bottom (Figure 5[b]), was developed by Wurster during the 1960s to significantly increase the collision probability between particles and coating droplets in order to improve the coating material efficiency and bring about a reduction in spray drying (dust reduction). The technique appeared very efficient for larger particles but presented high risk of agglomeration for smaller particles, due to the high concentration of wet particles at the bottom of the container. Wurster decided to put particles in motion using an insert. So, he invented the insert bottom spray coater, also known as Wurster (Figure 5[c]). The circulation of particles increases the drying rate and reduces the potential of agglomeration, leading to a great homogeneity in the coating quality (particles are surrounded by a smooth and continuous coating material). This apparatus is adapted for particles with various sizes and is used for moisture or oxygen barrier, for enteric or aesthetic coating with prolonged controlled release.

3. Rotor or Tangential Spray Processing

The rotor processing system (Figure 5[d]), was developed to produce coated particles with higher spherical shape and density. As is shown in Figure 5(d), the rotor reactor consists of a disk rotating in the fluidizing chamber. The combination of the rotation and the airflow provides the above specific properties. The coating film quality is similar to those obtained with a Wurster reactor. The main limitation of this design is the high agitation in the reactor that limits its application to coating materials that are not too crumbly or friable.

A comparison of different fluid-bed coating systems [8] shows that the type of process will most likely influence performance characteristics. But what must be kept in mind is that each system can be used successfully with an understanding of its advantages and limitations.

B. Improvement of the Performance of the Fluid-Bed Coating Process

Fluid-bed coating is still an empirical unit operation, which requires, after formulation, some feasibility trials and the theory of its scale-up is yet to be established. Some major investigations have been carried out by various research groups to master this technology. These investigations are favored by the development of technology, which allowed the development of a new generation of sprayers, nozzles, air filters, and air distributor plates, with high performance. The scope of our research includes working on the development of effective criteria of performance to assess the success of any improvement approach. It appears that any coating process can be well-assessed by three efficiency criteria, which are:

- E_c, the material efficiency, generally named coating efficiency [9]
- E_e, the energetic or thermal efficiency [10]
- E_q, the quality efficiency, which definition cannot be generalized since it is related to a required or adequate property.

There are many ways to improve a given fluid-bed coating system but the best ways are based on the process itself (design and modeling followed by automation) and on the coating material.

1. Optimization by Material Efficiency Improvement (Hot Melt and Dry Coating)

For most of the fluidized bed, the coating solution must have a low viscosity in order to be pumped. For this, the coating material is generally dissolved at a low rate (2 to 10%; this rate can be increased to 30% for dispersion in a latex or pseudolatex system) in the adequate solvent, which is not always suitable. During the coating process, a lot of energy is consumed for the evaporation of the large amount of solvent and the global material efficiency is low. The hot-melt coating can be an alternative to such situations. It can take place in a top, bottom, or rotor reactor, though the top spray process is the process most adopted for hot melt. Its specificity is such that, the coating material, melted by heating and sprayed on particles, is directly solidified by cold air rather than by drying. This confers to hot melt several important production advantages: (1) sprayed liquid = 100% coating agent, (2) short processing time, (3) no drying step required, and (4) no solvent used, that is, low cost, flexible and consistent, the recovery of the active ingredients is obtained by temperature release. Its main limitation is that it is not suitable for coating heat-sensitive (biological product) products where the dry coating system looks promising. Dry coating (which is explained in detail in another chapter) presents the same features as hot-melt coating with the difference that the product is not wetted and the coating is achieved by depositing powder on the core using a reduced volume of plasticizer.

2. Optimization by Design and Modeling

The fluid-bed process has been permanently upgraded, through the different types as mentioned above, and the Wurster looks like a finalized batch system from the design point of view for coating. The next step is the development of a continuous fluid bed that will effectively impose coating in the food industry. But this requires the optimization of the batch process operation and a few researchers [11–15] have carried out some significant investigations for this purpose by modeling. Prior to modeling, a number of works are in progress to understand the process, characterizing by means of in-line measurements [16], the aerodynamics and hydrodynamics of air and particles in the system. All this leads to some significant models, that is, those that can be considered as closely correlated to experimental data, from the droplet characterization, the particle velocities in different areas of the fluid bed, to the heat and mass transfer. These models are not all unique and some of them may be found in another form, the tendency being to derive simple models that can be used for process control, that is, the ability to automatically launch and conduct the fluid bed just by entering data concerning particles and coating material properties.

a. Coating Droplet Size. The first important characteristic is the droplet size produced from pneumatic nozzles. It may be predicted by the following correlation (Equation [5]), [17]. Note that this equation depends on the type of spray nozzle.

$$d_{\mathrm{g}} = \frac{585.10^3.\sqrt[3]{\sigma}}{V_{\mathrm{rel}}.\sqrt{\rho}} + 597\left(\frac{\mu}{\sqrt{\sigma\rho}}\right)^{0.45}\left(\frac{1000.Q_{\mathrm{sol}}}{Q_{\mathrm{a}}}\right)^{1.5} \tag{5}$$

where σ is the fluid surface tension (N/m), ρ the fluid density (kg/m^3), μ the fluid viscosity (mPa/sec), Q_{sol} the fluid volumetric flow rate (m^3/sec), Q_{a} the air volumetric flow rate (m^3/sec), and V_{rel} is the relative velocity $\approx$ outlet air velocity (m/sec).

b. Evaporating Time. The evaporating time is given by Equation (6) [18] (neglecting vapor pressure and low Reynolds number).

$$t_{\mathrm{total}} = \frac{\lambda\rho_{\ell}\cdot(d_0^2 - d_{\mathrm{c}}^2)}{8K_{\mathrm{d}}(T_{\mathrm{a}} - T_{\mathrm{s}})} + \frac{\lambda d_{\mathrm{c}}^2\rho_{\mathrm{p}}(X_{\mathrm{c}} - X_{\mathrm{f}})}{12K_{\mathrm{d}}\Delta T_{\mathrm{av}}} \tag{6}$$

where d_{c} is the droplet diameter at critical point (m), d_0 the capillary diameter (m), K_{d} the thermal conductivity, ρ_ℓ the density of liquid (kg/m^3), ρ_{p} density of particle (kg/m^3), X_{c} critical moisture content (%), X_{f} final moisture content of the dried particle (%), T_{a} air temperature (°C), T_{s} droplet surface temperature (°C), T_{av} average temperature (°C), and λ is the latent heat of vaporization.

c. Mass Flow Rate. The flow rate (Q_{ms} [kg/sec]) is approximated by the minimum spout flow rate (Equation [7]) [19].

$$Q_{\mathrm{ms}} = \rho_{\mathrm{p}}\cdot 5.92\cdot 10^{-5}\left[\frac{d_{\mathrm{p}}}{\phi D_{\mathrm{c}}}\right]^{0.05}\left[\frac{D_{\mathrm{i}}}{D_{\mathrm{c}}}\right]^{-2.6} \tag{7}$$

where d_{p} is the particle diameter (m), D_{i} the equivalent diameter of the bed (m), D_{c} the equivalent diameter of the air slot (m), and ϕ is the sphericity of the particle.

There are various other parameters, not mentioned here, whose model strongly depends on the type of fluid bed and the design, for example, particle velocities, the residence time, etc. [20].

C. Coated Powder Characterization

Among the three types of efficiency mentioned earlier, quality efficiency is probably the most difficult to define as it is related to required or adequate properties of the coated particles. These characteristics can give some information about the effectiveness of coating and its assessment and about the functional properties of the coated powder. Some useful characteristics of coated particles are described below.

The release behavior is the most important characteristic of the capsules. Capsules, which are protective barriers for various purposes (to oxygen, moisture, etc.),

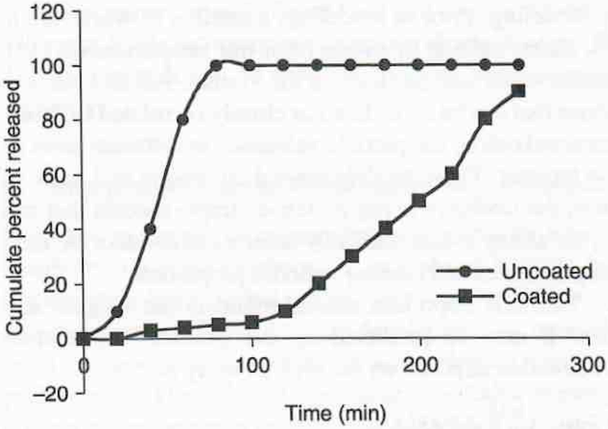


Figure 6 Released curve of a chocolate powder coated with starch.

are designed to release the core slowly (diffusion) or suddenly (shell dissolving or breakage) by various mechanisms: heating, dissolution, mechanical or chemical rupture, shell modification by pH, etc. There are many ways to measure the barrier properties of a shell material in accordance with the purpose of this barrier and the trigger event. Most of the time, the coated particles are placed in an environment whose properties are chosen to correspond with the application conditions; then the diffused core or the dissolved shell materials in the medium are quantified as a function of time. Figure 6 presents an example of a released curve obtained by dissolution of a coated chocolate powder in water under gentle agitation.

The size of capsules during coating is the most measured characteristic of particles. Its use in coating assessment requires very sensitive measurement methods as the final layer of the coating is only about 25 μm. Using a microscope is the best measurement method for this purpose but it is still a cumbersome technique and it is here that the light scattering technique of size analysis can help efficiently.

The morphology of the capsule can be a quality criterion of a coating operation when it is directly measured in parallel with the size. This is the case of the external capsule structure. The measurement of the internal structure requires the cutting or breaking of a number of particles to examine the inner surface of the capsule shell. This is generally done by imbedding the capsules in an appropriate medium that can solidify easily, then the solidified medium is cut into slices on which some cut capsules can be seen and analyzed using optical or scanning electron microscopy. There is always a correlation between the internal structure and the capsules' properties that are targeted, especially stability and release behavior.

The strength of the capsule is a mechanical property that is required to predict the behavior of the coated food powders during their storage or, the process in which they are involved. This parameter is crucial if the mechanical breakage is the trigger event for release. There are a number of methods to characterize the strength of a powder. Most of them are based on axial compression of a single capsule or the bulk powder [21], leading to the determination of the maximum strength that can be supported by the capsules without any damage. Others, called friability or abrasion tests are based on higher agitation (in a mixer) or percussion for a given time (corresponding to the handling and processing time), followed by an analysis of the agitation effect (size analysis, release test, etc.). They are all easy to apply where coarse particles are concerned.

Sensorial analysis of the capsule gives useful information about different aesthetic and sensorial properties of the coated powder such as the color, the shape, the taste, the flavor, and the roughness. The method consists in presenting different samples of the coated powder to a well-trained human panel (twelve or more persons). After testing the capsule in the desired conditions, the panel will select one or two samples that satisfy the objective. The tendency today is to develop some robots that can replace the human panel and give accurate information about those properties. This has been done with relative success since there are a number of robots that can identify or characterize individual aesthetic or sensorial properties but human intervention is still vital as the selection is based on the combination of various properties.

D. Coating Materials

It has been mentioned earlier that the role of coating is to fulfill a variety of aesthetic and protective purposes. The most commonly used coating materials in food and pharmaceutical industries are generally a reproduction of what is used in spray drying or cooling, for example, hydrocarbons, proteins, and lipids [22]. They must be in liquid form during the process in order to be pumped and for this they are dissolved or dispersed in a solvent. Their use also requires formulation and feasibility studies where the additives to be added and the optimum concentration are determined to keep the apparatus in good working order, for a good layering, and suitable final properties. Organic solvents are used in some specific cases, but water is preferred in the food industry (and more and more in the other industries) for three reasons: water is an edible, available, and low-priced solvent. It is easy to handle compared to other solvents. The new international regulations are becoming more and more severe about solvent release in the atmosphere and their concentration in food, drugs, and cosmetic products. The cheapest coating material is also preferred, as the food industry has become very competitive. The predominantly used materials to render the coating process economically feasible are:

1. For taste masking, carbohydrates (sugars [23], maltodextrins, starch, cellulose derivatives, and gums [24]), proteins (hydrolyzed gelatin), various hot melts (lipids and wax) and polymers (shellac).
2. For enteric coating, various polymers and hot melts [25,26], starch and cellulose derivatives.
3. For controlled release, cellulose derivatives, various hot melts and polymers [27,28].
4. For stability, starch and cellulose derivatives, hot melts, Arabic gum, and shellac [23,29–31].
5. For encapsulation of microorganisms for fermentation purposes, alginates and pectinates [27,28].

Note that there are various additives that are mixed to the initial formulation to homogenize (emulsifiers), and stabilize (thickeners) the mixture or to modify the rheological behavior of the coating solution (plasticizers) [32].

E. Guidelines for a Coating Operation

The role of the process manager is to create in the fluidized chamber propitious conditions for wetting and coating while keeping the whole layer in motion by flow-through gas. He can benefit from following some basic rules for a successful coating operation.

Most of the time, the engineer has to make an optimization in order to enhance the process performance. But in the case of fluid-bed coating, the efficiency of the process strongly depends in addition on the preparation phase, a step-by-step procedure that is the basis of successful coating:

- The first step is the description of the objectives of the coating operation — is it to protect the core, to mask a taste or flavor [29], to change the color or to favor a particular type of exchange, to improve some functional properties or some commercial aspects? etc. [30,33]. This step is vital for choosing the coating material and the type of capsule (matrix or reservoir system).
- The second step is to figure out how the capsules will be used or how the core will be released. This step is very important to define the shape, the particle size, size distribution, and the strength of the capsules [34].
- The formulation step is a critical step where compromises must be made with the composition of the coating solution (coating material, solvent, and additives such as plasticizer, stabilizers, texturizer, emulsifier, binders, flow enhancers, etc.) with regard to steps 1 and 2, the legislation, and the process operation. Preliminary tests of wettability and adhesion are sometime necessary to finalize this stage.

Thus, the relation between the objectives, the nature and the properties of particles, and the coating solution after formulation are determinants of the type of coating apparatus that will be chosen among a large variety of fluid beds. The choice of continuous fluid beds for food powder coating is indispensable.

VI. CONTINUOUS FLUID BED FOR FOOD POWDER COATING

The use of the continuous process in the food industry is widespread for coarse food material coating such as nuts, dried fruits, corn flakes, puffed grain, and so on. Conveyor belt processes and coating–blending drums are used for this purpose. The necessity to coat fine food particles continuously was pointed out in the 1970s with the emergence of the widespread use of spray drying and its derivatives: spray chilling, spray cooling, and prilling. These types of processes produce the matrix system (Figure 1[c]) with poor coating quality where parts of the core material are exposed to air and are not protected. They are limited to small particle size (<100 μm) [22].

For higher coating quality of fine particles, the continuous fluid-bed process appears to be an attractive alternative for food powder coating with low cost production. Indeed, a comparison of the characteristics of a batch fluid bed (Wurster) and a horizontal continuous one (Table 1) shows that a continuous process is the only alternative to allow application (low price) of fluid-bed coating for food powders. But, as it is mentioned in Table 1, the quality and the homogeneity of the final product is still much below par from the ones obtained with a Wurster system. A number of continuous fluid beds have been developed with more or less success.

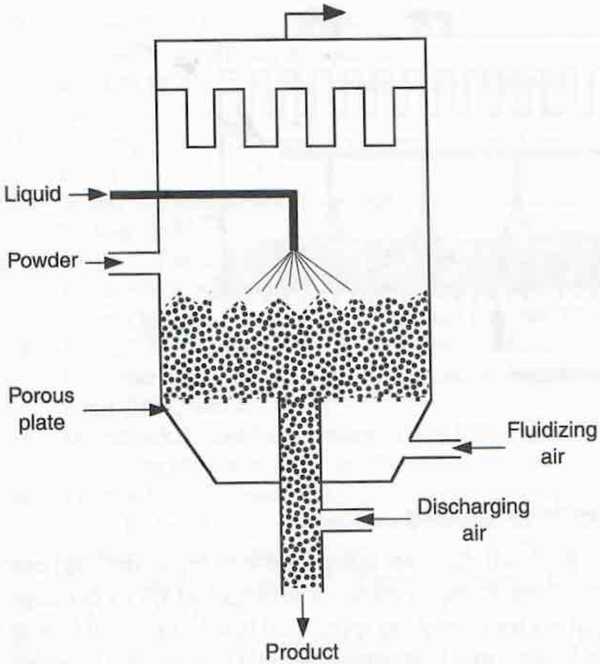


Figure 7 Monocell continuous fluid bed (top spray).

A. Single Bed Continuous Fluid Bed

This type of fluid bed operates along the same lines as the batch fluid-bed granulator, the difference being that particles with a predefined size are automatically discharged via the discharge pipe located in the center of the processing chamber (Figure 7). The other advantages are high output, compact design, predeterminable grain size, dust free and narrow particle size distribution, and low energy consumption. The main limitation of this method is that it is very difficult or impossible to meet contradictory specifications for agglomeration and solid bridges (layering) in a single cell.

B. Horizontal Continuous Fluid Bed

The real horizontal fluid bed (Figure 8) refers to a fluid bed with no obstacles in the system. Powder is admitted in the fluidizing chamber at one end from which it moves slowly during the desired process until it gets out at the other end. These types of fluid beds exist and are actually used in the food industry for various purposes. They are in general vibrating fluid beds with conveying belt and have been designed with a reasonable length since the 1970s. They were especially developed for granulation (instantizing) of powders after spray drying.

The main disadvantage of the real horizontal fluids bed is their length (several meters), which is necessary to allow the required residence time for the process. This disadvantage is worsened when the process involved is coating. A detailed analysis of the advantages and disadvantages of a horizontal fluid bed was done by Teunou and Poncelet [35], including comparison with the Wurster system and characteristics of an ideal fluid-bed coater.

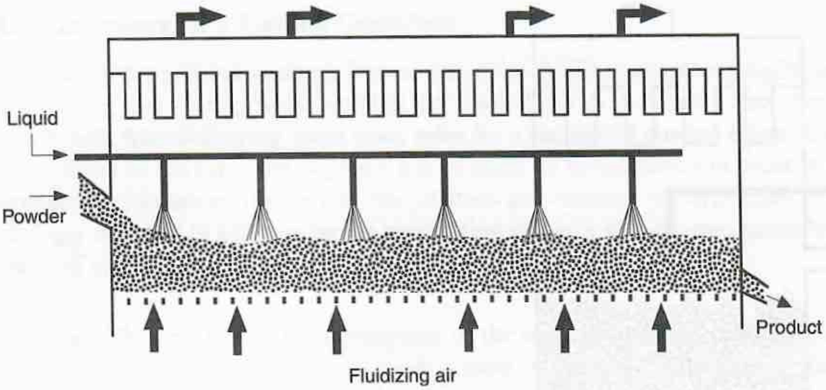


Figure 8 Horizontal continuous fluid bed (top spray).

C. Multicell Continuous Fluid Beds for Coating

Increasing the residence time in the fluid-bed chamber using fluid-bed properties [36] can reduce the length of the horizontal fluid bed. Rümpler made some progress [37] by developing a multicell fluid-bed coater, which is a horizontal top spray fluid bed divided into four or five compartments connected by regulating flaps. This apparatus leads to imperfect capsules where the coating material does not recover the total surface of core material (Figure 1[d]). However, these capsules are better than those obtained by spray drying and are adequate for physical protection (e.g., taste masking).

Another type of multicell fluid bed (presented by Leuenberger [38]) consists of several minibatches connected to each other with a transport, dosage, and classification system. This apparatus was promoted by Glatt [39], in order to combine advantages of batch and continuous process in the pharmaceutical industry. There is no published information about the quality of coating obtained by this system but it can be noted that this is an expensive installation.

VII. CONCLUSION

There is real demand for food powder coating to fulfill various purposes and these objectives are actually reached by spray drying or granulation with, in many cases, unsatisfactory results. This may explain why the actual volume of coated food powder is still relatively small compared to the huge potential that exists. Different types of fluid-bed coating have been proved not only to bring an adequate answer to these coating objectives but also to be too expensive techniques that cannot meet the main requirement of foodstuff, that is, low prices. The challenge today is to focus on further equipment evolution (instrumentation and control) that may result in the improvement of the continuous fluid-bed coating and its application to food powder coating.

REFERENCES

1. Arshady, R. Microcapsulation for food. *J. Microencapsulation* 4: 413–435, 1993.
2. Dezarn, T.J. Food ingredient encapsulation. Ed. Plach SJ. ACS Symposium Series-Washington DC pp. 74–86, 1995.

3. Geldart, D., Ed. Single particles, fixed and quiescent beds. In: *Gas Fluidisation Technology*. Chichester: John Wiley & Sons, 1987.
4. Jones, D.M. Air suspension coating for multiparticulates. *Drug Develop. Ind. Pharm.* 20: 3175–3206, 1994.
5. Geankoplis, C.J. *Transport Processes and Unit Operations*. 3rd ed. New Jersey: Prentice Hall Inc., 1993.
6. Briant, J. *Phénomènes d'interface — agent de surface — principe et mode d'action*. Paris: Technip, 1989.
7. Yvon, J., Thomas, F., Villieras, F., and Michot, L.J. Surface-activity of water. In: *Handbook of Powder Technology. Vol. 9: Powder Technology and Pharmaceutical Processes*. Eds. Chulia D., Deleuil M., and Pourcelot Y. Netherlands: Elsevier, 1994.
8. Jones, D.M. Considerations for various fluid bed techniques. Proceedings of Technological training center on current practices in fluid bed drying granulating and particle coating technology. Basel, 2001, Sec. 4.
9. Dewettinck, K. and Huyghebaert, A. Top-spray fluidised bed coating: effect of process variables on coating efficiency. *Food Sci. Technol. lwt* 31: 568–575, 1998.
10. Filkova, I. and Munjundar, A.S. Industrial spray drying systems. *Handbook of Industrial Drying*. Vol I. In: Ed. A.S. Mujumdar. New York: Marcel Dekker, 1995, pp. 263–307.
11. Alden, M., Torkington, P., and Strutt, A.C.R. Control and instrumentation of a fluidised-bed drier using the temperarture-difference technique. I. Development of a working model. *Powder Technol.* 54: 15–25, 1987.
12. Diego, L.F., Gayan, P., and Adanez, J. Modelling of the flow structure in circulating fluidised beds. *Powder Technol.* 85: 19–27, 1995.
13. Dewettinck, K. and Huyghebaert, A. Fluidised bed coating in food technology. *Trends Food Sci. Technol.* 10: 163–168, 1999.
14. Fyhr, C. and Kemp, C. Mathematical modeling of batch and continuous well-mixed fluidized bed dryers. *Chem. Eng. Process.* 38: 11–18, 1999.
15. Kusharski, J. and Kmiec, A. Hydrodynamics: heat and mass transfer during coating of tablets in a spouted bed. *Can. J. Chem. Eng.* 61: 435–439, 1993.
16. Masters, K. *Spray Drying*. London: Leonard Hill Books, 1979, p. 702.
17. Masters, K. Drying of droplets/sprays. In: *Spray Drying Handbook*. New York: John Wiley & Sons, 1988, pp. 298–342.
18. Mörl, L. and Drechsler, J. Using Lasentec FNRM in-process particle characterisation in fluid bed application – Preparing for Process Control. *Lasentec Technical Abstract*, M-2-007 (http://www.lasentec.com/M-2-007_abstract.html).
19. Rocha, S.C.S., Taranto, O.P., and Ayub, G.E. Aerodynamics and heat transfer during coating of tablets in two-dimensional spouted bed. *Can. J. Chem. Eng.* 73: 308–312, 1995.
20. Valenti, C. Etude d'un rocédé d'enrobage en lit fluidisé: le procédé Wurster. Thèse. Nancy: Université Henri Poincaré- I, 1998.
21. Shubert, H. Food particle technology. part II. Properties of particles and particulate food systems. *J. Food Eng.* 6: 1–32, 1987.
22. Jacson, L.S. and Lee, K. Microencapsulation in food industry. *Lebensm.-Wiss. U. technol.* 24: 289–297, 1991.
23. Buckton, G. and Darcy, P. The influence of additives on the recrystallisation of amorphous spray dried lactose. *Int. J. Pharm.* 121: 81–87, 1994.
24. Thevenet, F. Acacia gums stabilizers for flavor encapsulation. *Am. Chem. Soc.* 590: 37–44, 1988.
25. Baldwin, E.A., Nisperos, M.O., Hagenmaier, R.D., and Baker, R.A. Use of lipid in coatings for food product. *Food Technol.* 54(6): 56–64, 1997.
26. Dian, N.L.H.M., Sudin, N., and Yusoff, M.S.A. Characteristics of microencapsulated palm-based oil as affected by type of wall material. *J. Sci. Food Agric.* 70: 422–426, 1996.
27. Gareth Leach, G. Production of a carotenoid-rich product by alginate entrapment and fluid bed drying of dumalielle salina. *J. Sci. Food Agric.* 76: 298–302, 1998.

28. Vilstrup, P. *Microencapsulation of Food Ingredients.* 1st ed. Surrey: Leatherhead, 2001.
29. Brake, N.C. and Fennema, O.R. Edible coatings to inhibit lipid migration in confectionary product. *J. Food Sci.* 58(6): 1422–1425, 1993.
30. Guilbert, S. and Gontard, N. Prolongation of the shelf-life of perishable food product using biodegradable films and coatings. *Lebensm-Wiss. U. Technol.* 29: 10–17, 1994.
31. Keogh, M.K. and O'Kennedy, B.T. Milk fat microencapsulation using whey proteins. *Int. Dairy J.* 9: 657–663, 1999.
32. Rizzotti, R. Les agents de texture épaississants. gélifiants. *Stabilisants*. IAA 563–573, 1994.
33. Janovsky, C. Encapsulated ingredients for baking industry. *Cereal food World* 38: 85–87, 1993.
34. Wan, L.S.C., Heng, P.W.S., and Chia, C.G.H. Spray drying process for microencapsulation and the effect of different coating polymers. *Drug Develop. Ind. Pharm.* 18: 977–1011, 1992.
35. Teunou, E. and Poncelet, D. Batch and continuous fluid bed coating: review and state of the art. *J. Food Eng.* 53: 325–340, 2002.
36. Dumon, R. *Les Applications Industrielles des Lits Fluidisés*. Paris: Masson, 1981.
37. Rumpler, K. Continuous fluid bed lipid coating of particles. Proceedings of the 9th International Glatt Symposium, Weimar, 1999.
38. Leuenberger, H. Pseudo-continuous fluid bed processing: The Glatt multi cell concept. Proceedings of the 10th International Glatt Symposium on Process Technology, Prague, 2000.
39. Glatt International (2002). Spray granulation dryers (AGT system) in the ceramic industry. Technical information (http://www.glatt.de).