ELSEVIER

Journal of Food Engineering 53 (2002) 325–340

JOURNAL OF
FOOD
ENGINEERING

www.elsevier.com/locate/jfoodeng

Batch and continuous fluid bed coating – review and state of the art

E. Teunou *, D. Poncelet

Département de Génie des Procédés Alimentaires, École Nationale d'Ingénieurs des Techniques des Industries Agricoles et Alimentaires,
Rue de la Géraudière, BP 82225, 44322 Nantes Cedex 3, France

Received 27 April 2001; accepted 14 September 2001

Abstract

In this paper is presented a varied description of the fluid bed process for coating or air suspension coating with emphasis on the most efficient batch fluid bed apparatus (the wurster system) and the ideal continuous fluid bed. Phenomena involved in the process of coating fluidised solid particles are studied. The problem of the application of this technology to coat food particles, in terms of feasibility and profitability, is discussed. A comparison between the batch and the continuous systems will bring out the fact that the continuous fluid bed process is the economically suitable solution for coating food powders, but there are a number of problems that must be overcome to get the ideal or efficient continuous system, which does not exist yet. A short review of all these problems is presented. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Coating process; Fluidised bed; Food powders; Batch and continuous

1. Introduction

After the development of granulation in the nineties, the tendency today is to protect the active components of many foodstuff (Chessé, 1999), ingredients or additives that are in powder form. Every year, tons of food powders are required with some specific properties that the natural product does not offer. Encapsulation provides one means of meeting this demand. It is a process where thin film 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 flavours; protect unstable ingredients from degradation factors, such as heat, moisture, air and light. It can provide controlled or delayed release and reduce hygroscopicity. It also helps in changing the physical characteristics of the original material, such as flowability and compression, dust reduction and density modification (Dezarn, 1995). In the food industries, the method is applied to encapsulate enzymes, vegetable proteins, yeast, bacteria and aromas in maltodextrine or arabic gum matrices and film coatings of extruded products by lipids, resins, polysaccharides and proteins.

There are various processes employed for encapsulation and coating of food ingredients or additives (Arshady, 1993). They all will not be described here but one could mention extrusion, solvent extraction, coacervation, cocrystallisation, spray drying, fluidised bed coating, mixing and adhesion in rotating drums, etc.

When it comes to coating dry solid particles (powders), i.e. the engulfing of particles into a coating material, fluid bed coating is best. This type of coating process leads to capsules called a reservoir system where the particles are surrounded by a layer (Fig. 1(a)) or multiple layers (Fig. 1(b)) of coating materials. The fluid bed technology applied to coating, which is still a batch process, is expensive and time consuming process, but is actually used in pharmaceutical and cosmetic industries which are able to compensate the cost of the process by the high price of their final product. The batch system has been currently upgraded to improve its performance (residence time distribution and homogeneity of the coating layer) and to avoid agglomeration. Among the existing systems, top spray, bottom spray, side spray with rotating disk (Ormos, 1994), the "wurster" fluid bed system is the most adequate for particle coating.

It is well known that one of the imperative targets for food industries is to offer foodstuff at low prices. That

---

[*] Corresponding author. Fax: +33-2-51-78-54-54.
E-mail address: teunou@enitiaa-nantes.fr (E. Teunou).

PII: S0260-8774(01)00173-X

Nomenclature

Ar	Archimedes number, dimensionless
C_D	drag coefficient, dimensionless
D	diameter of the fluid bed (m)
Dg	droplet size produced from pneumatic nozzles (m)
d_c	droplet diameter at critical point (m)
D_c	equivalent diameter of the air slot (m)
D_i	equivalent diameter of the bed (m)
Dm	coating solution dry matter content (kg/kg)
d_p	particle diameter (m)
d_v	diameter of an equivalent sphere (m)
d_0	capillary diameter (m)
e	thickness of the coating material (μm)
E_c	material efficiency, dimensionless
E_e	energy efficiency, dimensionless
E_p	productivity efficiency, dimensionless
E_q	quality efficiency, dimensionless
g	standard acceleration of gravity (m/s^2)
H	height of the bed (m)
H_a	length of the annular zone (m)
H_c	distance covered by particle in the central tube (m)
K_d	thermal conductivity (w/m °C)
L	average total distance covered by particles during coating (m)
l_{cycl}	average distance travelled by particles during one cycle wurster fluid bed (m)
m	total mass of particle in the fluid bed (kg)
N	average number of cycles travelled by particles, dimensionless
P_{pulv}	pulverisation pressure (bar)
Q_a	air volumetric flow rate (m^3/s)
Q_{ms}	mass flow rate of particles in the fluid bed (kg/s)
Q_{sol}	fluid volumetric flow rate (m^3/s)
Re_p	Reynolds number for particles, dimensionless
Sp	specific surface of particles (m^2/kg)
T_a	air temperature (°C)
T_{av}	average temperature (°C)
t_a	residence time in the annular zone (s)
t_c	residence time in the central tube (s)
t_{coat}	total coating time (min)
t_{cycl}	average cycling time of particles in the wurster fluid bed (s)
t_d	residence time in the dragging zone (s)
T_s	droplet surface temperature (°C)
t_{total}	evaporating time (s)
U	is the relative velocity of gas (m/s)
U_{cf}	overall fluidising velocity at which all particles are fully supported (m/s)
U_{mf}	minimum fluidisation velocity (m/s)
U_{mfi}	minimum fluidisation velocity for particles of size d_{pi}
U_p	particle velocity in the central tube of the wurster fluid bed (m/s)
U_t	settling or terminal velocity of particles in the annular zone (m/s)
w	coating content of the capsule (kg/kg)
W_c	deposited mass of coating (kg)
W_{cs}	mass of coating solution (kg)
Wm	wetting energy (J)
W_p	mass of core material (kg)
X_c	critical moisture content (%)
X_f	final moisture content of the dried particle (%)
x_i	particle fraction of size d_{pi}
Greeks	
Δp	pressure drop in a cylindrical fluid bed (Pa)
ϵ	void fraction, dimensionless
ϕ	sphericity of the particle, dimensionless
γ_{sv}	interfacial tension between solid and vapour (J)
γ_{sl}	interfacial tension between solid and liquid (J)
γ_{lv}	interfacial tension between liquid and vapour (J)
λ	latent heat of vaporisation (J/kg)
μ	fluid viscosity (kg/m s)
μ_g	gas viscosity (kg/m s)
μ_l	liquid viscosity (kg/m s)
μ_{app}	apparent viscosity of a fluid bed (kg/m s)
ρ	fluid density (kg/m^3)
ρ_{app}	apparent specific weight of a fluid bed neglecting the air density (kg/m^3)
ρ_{bulk}	bulk density of the granular material (kg/m^3)
ρ_g	gas density (kg/m^3)
ρ_l	density of liquid (kg/m^3)
ρ_p	particle density (kg/m^3)
σ	fluid surface tension (N/m)

means, despite its high performance, the use of wurster coating in the food industries is problematic because the actual cost of the final coated powder, as will be seen latter (Table 1), is too high. In order to reduce the cost of production, the continuous process appears to be an attractive alternative for food powder coating.

The objectives of this paper is to compare the batch and the continuous fluid beds processes to show to what extent the continuous multicellular or horizontal fluid bed is viable for coating food particles. Emphasis will be placed on problems encountered with this process and the discussion is focussed on their solution.

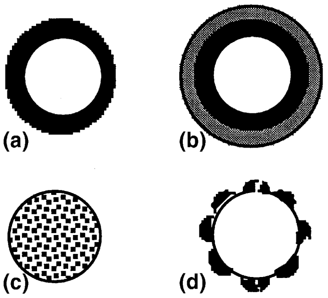

Fig. 1. Different types of capsules: (a) reservior system; (b) reservior system with multiple layer; (c) matrix system; (d) imperfect capsule.

2. Fluidisation

2.1. Fluid bed description

The principle of a fluid bed is to maintain particles in suspension in a close area by blowing air through the powder bed. The state of the fluid bed depends on the air velocity and the powder properties. Many authors (Geldart, 1986; Jones, 1994; Kunii & Levenspiel, 1993) have described different configurations as a function of air velocity (Fig. 2). The main important air velocities for a fluid bed are the minimum fluidisation velocity U_{mf} and the settling or terminal velocity U_{t}. The velocity, U_{mf}, that leads to a stable fluid bed (Fig. 2(e)), is used for processes such as drying, coating, granulation, agglomeration, etc.

Its equation is defined by the following:

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

where ρ_{g} is the gas density (kg/m^3), ρ_{p} the particle density (kg/m^3), d_{p} the particle diameter (m), d_{v} the diameter of an equivalent sphere (m) and μ_{g} the gas viscosity (kg/m s).

Eq. (2) is used for particles larger than 100 μm.

$$U_{\mathrm{mf}} = \frac{\mu_{\mathrm{g}}}{\rho_{\mathrm{g}} d_{\mathrm{v}}} \{(1135.7 + 0.0408 Ar)^{1/2} - 33.7\} (\mathrm{m/s})$$
$$d_{\mathrm{p}} > 100\ \mu\mathrm{m}, \qquad (2)$$

where Ar is the Archimedes number

$$Ar = \frac{\rho_{\mathrm{s}} d_{\mathrm{v}}^3 (\rho_{\mathrm{p}} - \rho_{\mathrm{g}}) g}{\mu^2}.$$

The settling velocity (Eq. (3)), U_{t} is the air velocity over which dragging or transportation of the particles (for example, pneumatic conveying) occurs (Fig. 2(f)).

$$U_{\mathrm{t}} = \left[\frac{4 g d_{\mathrm{p}} (\rho_{\mathrm{p}} - \rho_{\mathrm{g}})}{3 \rho_{\mathrm{g}} C_{\mathrm{D}}} \right]^{0.5} \ (\mathrm{m/s}), \qquad (3)$$

where C_{D} is the drag coefficient which 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 Geankoplis (1993).

2.2. Powder classification regarding fluidisation

Powders can be classified regarding their properties and their functionality. Geldart's works (1986) have shown that, for the fluidisation process, powders can be classified into four groups (Fig. 3) according to fluid density and the particle size and density. For example, powders from group C are cohesive and difficult to fluidised, while powders of group A present the aeration property required for coating purposes. Other classification systems, based on the flow regime, are mentioned by Geldart (1986). These charts are very helpful for quick decisions.

2.3. Properties of a fluid bed

The fluid bed is still a very complex unit operation, mostly because the trajectories of particles in the fluid bed are not predictable. But it has found so many applications because of its particular properties and different behaviours, which provide a process having:

- Limited pressure drop,
- temperature homogeneity,
- fast heat and mass transfer,
- easy control of flow rate and reaction kinetics.

Table 1
Comparison of two types of fluid beds batch and continuous [a]

	Batch (wurster)	Continuous (horizontal)
Volumes	120 l	120 l
Flow rate (kg)	50 kg/h	100 kg/h
Price of the basic equipment in 1999	1,100,000€	610,000€
Cost of the coating operation	≈ 2.1€/kg	≈ 0.6€/kg
Product quality	Excellent true reservoir capsules (Fig. 1(a) and (b)) uniform batch	Passable Presence of capsules with incomplete layer (Fig. 1(d)) heterogeneous product

[a] *Notes*. All information mentioned in this table are derived from Glatt Pharmatech data. Glatt Pharmatech S.a.r.l., Parc Technologique rue Louis Neel 21000 Dijon.

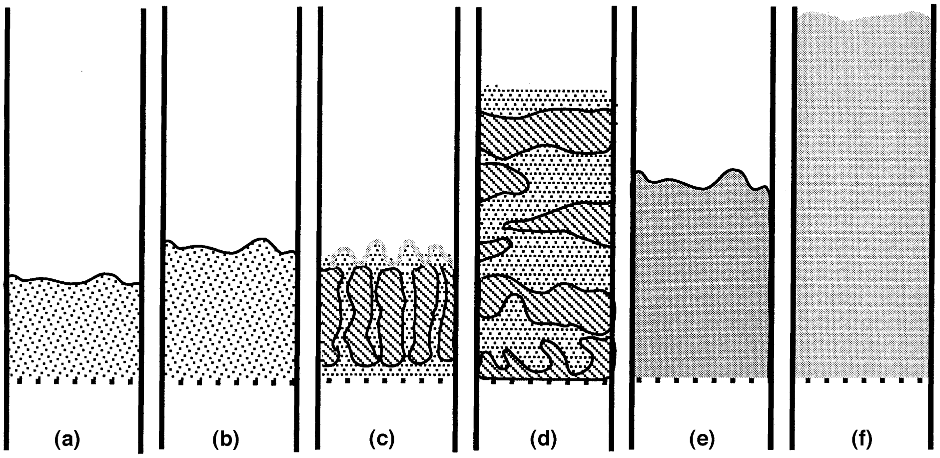

Fig. 2. Different configurations of a fluid bed: (a) fised bed; (b) expension; (c) channelling; (d) slugging; (e) stable fluid bed; (f) conveying.

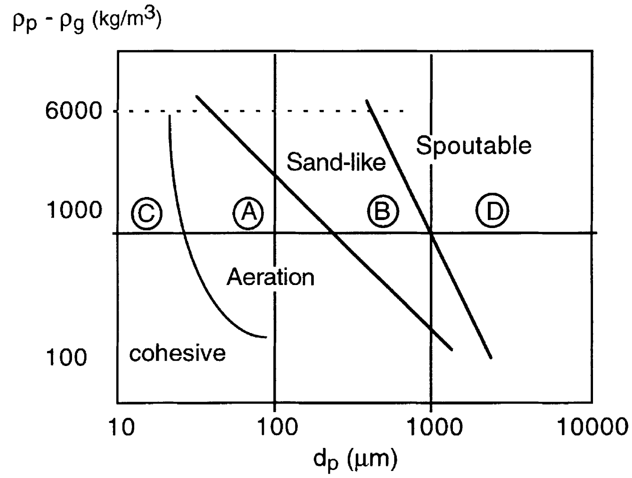

Fig. 3. Geldart's classification of powders.

Indeed, a fluidised bed presents similar properties to a fluid (Dumon, 1981) because of the high agitation in the system:

- The density or apparent specific weight is given by Eq. (4), neglecting the air density:

$$\rho_{\text{app}} = (1 - \varepsilon)\rho_{\text{p}} \ (\text{kg/m}^3). \tag{4}$$

- The apparent viscosity proposed by Kunitz (in Dumon, 1981) can be written as:

$$\mu_{\text{app}} = \frac{1 + 0.5(1 - \varepsilon)}{\varepsilon^4} \ (\text{kg/m s}). \tag{5}$$

- The pressure drop in a cylindrical fluid bed (commonly used), and the case of a laminar flow is given by the Poiseuille equation:

$$\Delta p = \frac{32\mu_{\text{app}} UH}{gD^2} \ (\text{Pa}). \tag{6}$$

A fluidised bed also behaves like a liquid at the beginning of boiling, i.e.:

- The upper limited surface of the fluid bed remains horizontal if the bed is inclined (Fig. 4(a));
- an object, placed in the fluid bed, will float depending on its density (Fig. 4(b));
- particles will flow through any hole in the side wall of the fluid bed (Fig. 4(c));
- when a cylinder is immersed in the fluid bed, there is an intense circulation of particles passing trough the cylinder without any external supply of energy (Fig. 4(d)).

It will be seen later how a judicious exploitation of these properties and characteristics could help in the design of an efficient fluid bed for coating.

Fluidisation, by its principle, appears to be a segregationist system that must be well designed and conducted in order to give homogeneity. For example, materials having a large size distribution are subject to separation at velocities close to the minimum fluidising velocity, U_{mf}. In this case, Geldart suggests the use of an overall fluidising velocity U_{cf} at which all particles are fully supported.

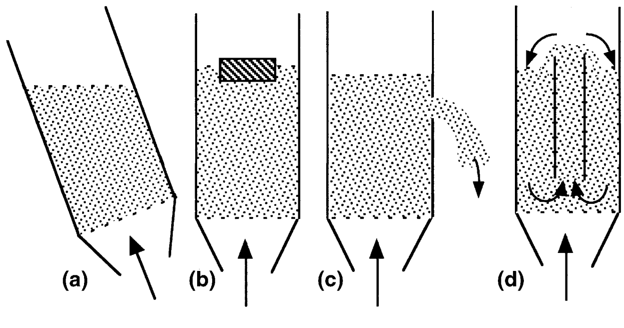

Fig. 4. Properties of a fluid bed.

$$U_{cf} = \sum x_i U_{mfi} \text{ (m/s)}, \tag{7}$$

where U_{mfi} and x_i refer to velocity and fraction of particles with size d_{pi}. This appears to give reasonable agreement with experimental values, even at high pressures.

3. Batch coating of powders in a fluid bed

3.1. Fluid bed coating, the state of the art

Agglomeration, granulation and coating processes are the main application of a batch fluid bed today in the food industry (Becher & Schlünder, 1997; Dewettinck & Huyghebaert, 1999; Härkönen, Koskinen, Linko, Siika-aho, & Poutanen, 1993). Most of the time the same apparatus is used for different applications (granulation, coating, agglomeration and drying). The following discussion will focus on different aspects of the coating process.

3.1.1. Principle of coating in a fluid bed

The principle of coating in a batch fluid bed is summarised in Fig. 5. Particles to be coated are introduced into the cell and fluidised by an air current. The coating material is pumped to a nozzle and sprayed on the particles. During this process, there is a homogeneous layering of the coating material on the particles and a tendency for particles to agglomerate to each other. 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 one hand and agglomeration of wetted particles on the other hand. A brief description of all phenomena during this process gives a better understanding of the situation.

3.1.2. Phenomena during coating process

There are three phases present in a fluid bed: solid (particles), liquid (liquid coating materials) and gas (the fluidising air). During the coating operation, there are a number of phenomena, due to interaction between these phases. These phenomena are classified chronologically in the following but most of the time many of them take place simultaneously. They are:

- Air suspension of particles in the coating chamber (particles dynamics).
- Spraying of coating material as droplets with the objective to increase the probability of particle-droplet impacts but droplets can easily be dried (heat transfer) before the collision with the particle. In this case there is no coating.
- 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, coalescence of droplets occurs on the particle surface before drying (heat transfer) of the droplets to form a layer.
- Layering or superposition of different layers of droplets around the particle resulting in a homogeneous reservoir system, i.e. a real coating. After several cycles of wetting-drying, a continuous film will be formed, with a controlled thickness and a composition depending on the materials used. It is mainly at this stage that the tendency for agglomeration between two or several particles is high.

The success of the coating operation depends on the spreading of the droplet on the particle surface after collision. This phenomenon is a function of the wettability of particles by droplets and requires a wetting energy (Briant, 1989; Yvon, Thomas, Villieras, & Michot, 1994). There are numerous works published about the

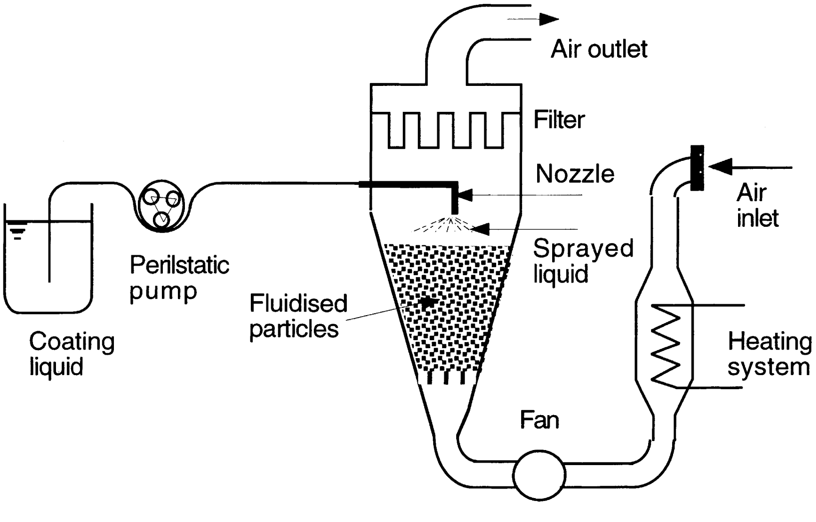

Fig. 5. A top spray fluid bed granulator or coater.

wettability of powders (Allais, 1997; Link & Schlunder, 1997) and the strength of the bonds between closed particles (Schubert, 1981). To summarise, this energy depends on the contact angle between the three phases present (solid–liquid–gas). This angle itself depends on chemical and physical characteristics of the liquid and the particle surface (hygroscopicity, roughness). Under some conditions and assumptions (flat, homogeneous, isotropic and non-deformed surface), the wetting energy can be expressed as a wetting coefficient Wm:

$$\mathrm{Wm} = \gamma_{\mathrm{sv}} - \gamma_{\mathrm{lv}} - \gamma_{\mathrm{sl}}\ (J), \tag{8}$$

where γ_{sv} is the interfacial tension between solid and vapour (J); γ_{sl} the interfacial tension between solid and liquid (J); γ_{lv} the interfacial tension between liquid and vapour (J). A liquid can wet a surface if the wetting modulus is larger than $0(\mathrm{Wm} > 0)$.

The role of the process manager is to create in the fluidised chamber suitable conditions for wetting and coating while keeping the whole layer in motion by the flow-through gas. The following will present some key points for a coating operation.

3.1.3. Basis of the coating operation

Most of the time, the engineer has to optimise the process in order to enhance the performance. However, 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 here called 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 flavour (Kester & Fennema, 1986), to change the colour or to favour a particular type of exchange, to improve some functional properties or some commercial aspects? (Guilbert, Gontard, & Gorris, 1996; Janovsky, 1993). This step is critical for the coating material choice 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 release. This step is very important to define the shape, the particle size, size distribution and the strength of the capsules (Chulia, 1994; Wan, Heng, & Chia, 1992).
- The formulation step is a critical step where compromises must be found between the composition of the coating solution (coating material, solvent and additives such as plasticiser, stabilisers, texturizer, emulsifier, binders, flow enhancers, etc.), the legislation and the process operation. Preliminary tests of wettability and adhesion are sometime necessary to finalise this stage.

In addition, the relationship 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 from a large variety of fluid beds outlined below.

3.2. Optimisation of the batch coating system

There are many ways to improve a given system and the success of this effort can be quantified if effective performance criteria are defined.

3.2.1. Performances of a coating operation

As mentioned above, there are many phenomena present during coating. The performance of the system should take into account all these aspects of the process but this is not the case at present. Most of the time the performance is defined as coating efficiency, E_{c} (Eq. (9)) (Dewettinck & Huyghebaert, 1999).

$$E_{\mathrm{c}} = \frac{W_{\mathrm{c}}}{W_{\mathrm{cs}}Dm}\ \text{(dimensionless)}, \tag{9}$$

where $W_{\mathrm{c}} = W_{\mathrm{p}}(w/(1-w))$ is the deposited mass of coating (kg), w the coating content of the capsule (kg/kg), W_{p} the mass of core material (kg), W_{cs} the mass of coating solution (kg) and Dm the coating solution dry matter content (kg/kg).

E_{c} is a type of material efficiency and its expression (Eq. (9)) shows that there is no information about the energy balance or the quality of the resulting capsules. The suggestion here is that coating performance be considered from general point of view and that at least four efficiencies be defined:

- E_{c}, the material efficiency, mentioned above as coating efficiency (Eq. (9)).
- E_{e}, the energy efficiency (Filkova & Munjundar, 1995).
- E_{q}, the quality efficiency, whose definition cannot be generalised since it is related to a required property.
- E_{p}, the productivity efficiency, which is simply defined as the total amount of coated material per hours. It is in fact the most important factor for scale up or industrial application.

A good definition of the performance criteria is essential for improvement assessment. The best way to improve a given system today is by design and modelling followed by automation.

3.2.2. Optimisation by design improvement

During recent decades, the development of technology has yielded an improvement of all aspects of fluid bed operation. New sprayers, nozzles, air filters and air distributor plates have emerged. This section focuses on the history of fluid bed application to coating and evolution of the design of fluid bed reactors for coating leading eventually to the insert bottom spray fluid bed.

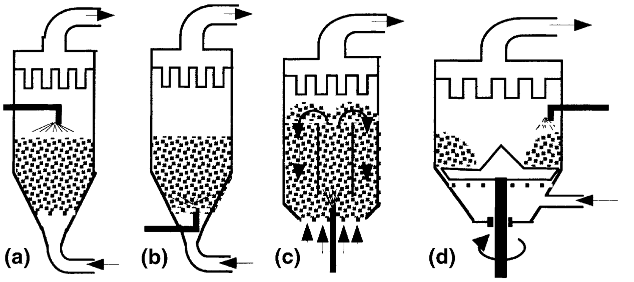

Fig. 6. Different types of batch fluid beds: (a) top spray; (b) bottoom spray; (c) wurster; (d) rotor with side spray.

In the fifties, coating was done in top spray granulators (Fig. 6(a)) where the spray nozzle is placed at the top of the fluid bed chamber. But the efficiency, in terms of deposited material and coating quality, was poor (spray drying of droplets and the subsequent fines production), leading to capsules with poor controlled release characteristics. So, despite its availability, its big capacity and the easily accessible sprayer, the top spray was not the one for coating.

During the sixties, The option, inspired by the Wurster works (Wurster, 1950) was to spray the coating liquid from the bottom (Fig. 6(b)). This so-called bottom spray system increases considerably the collision between particles and droplets and results in a larger coating material efficiency and a reduction in spray drying (dust reduction). This fluid bed was very efficient for tablet coating but for small particles, the risk of agglomeration was high because of the high concentration of wet particles. Wurster decided to use one property of the fluid bed described above (Fig. 4(d)) to put the particles in motion. He invented the insert bottom spray coater, also called the wurster system (Fig. 6(c)). The circulation of the particles increases the drying rate and reduces the potential for agglomeration, leading to a greater homogeneity in the coating quality (particles are surrounded by a smooth and continuous coating material). This apparatus is adapted for prolonged controlled release capsules and for particles with various sizes.

A fourth type of reactor, called the rotor system (Fig. 6(d)), was developed. As is shown in this figure, the rotor reactor consists in a disk rotating in the fluidising chamber. The combination of the rotation and the air flow provides specific properties such as higher spherical shape and density to the resulting coated particles. The coating film quality is similar to that obtained with a wurster reactor. The main drawback of this design is the high agitation in the reactor that limits its application to coating materials which are not too crumbly or friable.

3.2.3. Optimisation by material efficiency improvement

For most of the fluidised bed reactors (top, wurster or rotor) used as coaters, the coating solution must have a low viscosity to facilitate pumping. For that, the coating material is generally dissolved at a low concentration (0.5–4%) in the adequate but not always suitable solvent. 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. Hot melt coating can be an alternative to such a situation. It can take place in a top, bottom or rotor reactor, though, the top spray process is the main application method for hot melt processes because it offers the best configuration for particle cooling. Its specificity is that, the coating material, melted by heating and sprayed on to the particles, is directly solidified by cold air rather than drying. This confers on hot melt several important production advantages: short processing time, no particle shrinkage, no drying step required, low energy consumption, no solvent used, i.e. low cost, flexible and consistent.

Its main drawbacks are the size and density of the final capsule, the bed depth, air velocity and the bubble size. In addition, it is only suitable for fats, waxes and molten materials that are used in liquid coating, taste masking or drug release. For example it is unsuited for coating heat sensitive (biological product) products where the rotor looks promising.

Consequently, the best fluid bed design which is suitable for major coating purposes is undoubtedly the wurster. That is why the following section will focus on all possible improvements of this system.

3.2.4. Optimisation by modelling

Fluid bed manufacturers have permanently upgraded fluid beds in general and the wurster in particular, in such a way that this latter appears today almost like a finalised system from the design point of view for coating. The next stage now is to optimise the process operation and some researchers (Alden, Torkington, & Strutt, 1987; Dewettinck, Visscher, Deroo, & Huyghebaert, 1999; Diego, Gayan, & Adanez, 1995; Fyhr & Kemp, 1999; Kusharski & Kmiec, 1983) have carried on some significant investigations to this end. Their tools were experimental design plans and modelling. As mentioned in Section 3.2.2, the coating process is very complex because of the aerodynamics and hydrodynamics in the system and it is necessary to have a complete comprehension of the system prior to modelling. This can be achieved by a good experimental design plan.

3.2.4.1. Comprehension of the process. An insert bottom spray-wurster can be divided into four parts (as shown in the outline of a fluid bed in Fig. 7) which depend on each other, covered by particles in circulation:

- The dragging zone or the spouting zone (1), where particles are sucked by the air current to the entry

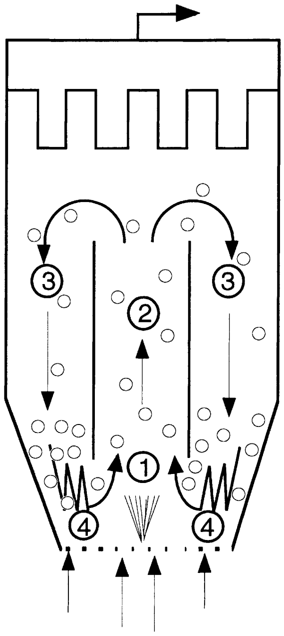

Fig. 7. Particle trajectories in different zones of a batch fluid bed.

of the insert cylinder. Particles are wetted in this area by the sprayed coating liquid.
- The inner cylinder zone (2), where particles are transported by pneumatic conveying. The drying process takes place in this area.
- The annular zone (3), where particles are falling downward towards the bottom of the fluidising chamber.
- The tampon zones (4) where particles are moving slowly in successive jumps towards the spouting zone.

Briefly, to achieve an excellent coating, the wetted particles must be dried during their ascent in the central tube. So the mean drying time can be considered lower than the time necessary for a particle to travel the along the central tube. Anyway, if wet particles reach the annular zone, they will stick to each others and agglomerate, because they are very close to each others and their velocity in this zone is low compared to that in the central tube (Table 2).

3.2.4.2. Significant models in coating operation.

3.2.4.2. Significant models in coating operation. In this section are summarised some significant models, i.e. those that can be considered as closely correlated to experimental data, for the droplet characterisation, the particle velocities in different areas of the fluid bed and the heat and mass transfer. These models are not all unique and some of them may be found in another form.

Droplet size. The first important characteristic is the droplet size produced from pneumatic nozzles. It may be predicted by the following correlation (Eq. (10)), given by Masters (1979). Note that this equation depends on the type of spray nozzle.

$$d_g = \frac{585\times 10^3\sqrt[3]{\sigma}}{U\sqrt{p}} + 597\left(\frac{\mu}{\sqrt{\sigma\rho}}\right)^{0.45}\left(\frac{1000Q_{\mathrm{sol}}}{Q_{\mathrm{a}}}\right)^{1.5}\ (\mathrm{m}), \qquad (10)$$

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

Evaporating time. Once droplets are formed the main criterion is their collision with the particles before their drying. The evaporating time can be used to calculate the drying time of the droplets and thus helps in defining spraying conditions for a particle/droplet collision before the drying of this latter. It can be expressed by the following equation (neglecting vapour pressure and low Reynolds number) given by Masters (1988).

Table 2
Measured and calculated parameters for coating of lactose by Eudragit (Experimental data from Valenti, 1998 and Guignon, Duquenoy, & Dumoulin, 2000)

Lactose				Eudragit		
Characteristics of the materials						
m (kg)	Sp (m^2/g)	ρ_{bulk}	d_{p}		Q_{sol} (g/min)	$P_{\mathrm{pulv.}}$ (bar)
0.2	0.168	710	200		8.74	0.8
Characteristics of the fluid bed coater						
	Q_{air} (m^3/h)	T_{a} (°C)	t_{coat} (min)	H_{c} (cm)	H_{a} (cm)	
	45	40	35	20	20	
Measured parameters						
	U_{p} (m/s)	U_{t} (m/s)	Q_{ms} (kg/s)	e (μm)		
	2.72	0.25	0.016	25		
Calculated parameters						
t_{c} (s)	t_{a} (s)	t_{d} (s)	t_{cycl} (s)	l_{cycl} (m)	N (–)	L (m)
0.073	0.8	11.79	$\approx$ 13	0.5	160	80

Remarks. Homogeneous coating with very few aggregates and no filter or nozzle obstruction.

$$t_{\text{total}} = \frac{\lambda \rho_1 (d_0^2 - d_c^2)}{8K_d(T_a - T_s)} + \frac{\lambda d_c^2 \rho_p (X_c - X_f)}{12K_d \Delta T_{av}} \ (s), \tag{11}$$

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 the density of particle (kg/m^3), X_c the critical moisture content (%), X_f the final moisture content of the dried particle (%), T_a the air temperature (°C), T_s the droplet surface temperature (°C), T_{av} the average temperature (°C) and λ the latent heat of vaporisation (J/kg).

Particle velocities. Once droplets are spread on particles, they must dry in a time smaller or at least equal to the time required for their transportation in the central tube, otherwise they will reach the annular area where they can agglomerate to each other. The residence time in the central tube can be calculated using the particle velocity (Valenti, 1998) in the central tube (assuming pneumatic transport and constant velocity in the tube).

$$-\frac{3}{4d_p\rho_p} C_D \rho_g (u_g - u_p)^2 + \left(1 - \frac{\rho_g}{\rho_p}\right) g = 0 \tag{12}$$

and

$$t_c = \frac{H_c}{u_p} \ (\text{s}), \tag{13}$$

$$t_a = \frac{H_a}{u_t} \ (\text{s}), \tag{14}$$

$$t_d = \frac{m}{Q_{ms}} \ (\text{s}), \tag{15}$$

where H_c is the distance covered by particle in the central tube (m), H_a the length of the annular zone (m), M the total mass of particle in the system (kg), t_c the residence time in the central tube (s), t_a the residence time in the annular zone (s), t_d the residence time in the dragging zone (s) and Q_{ms} the flow rate (kg/s). Knowledge of particle velocities and flow rate in different areas allows the calculation of different residence times (Eqs. (13)–(15)): velocity in the annular zone is equal to the falling velocity given earlier by Eq. (3). The velocity in the dragging zone is not constant and can only be derived from a mass balance or from the flow rate. The minimum spout flow rate (Eq. (16)) is a good approximation of the flow rate (Rocha, Taranto, & Ayub, 1995).

$$Q_{ms} = \rho_p 5.92 \times 10^{-5} \left[\frac{d_p}{\phi D_c}\right]^{0.05} \left[\frac{D_i}{D_c}\right]^{-2.6} \ (\text{kg/s}), \tag{16}$$

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 the sphericity of the particle.

Despite the fact that these models are very helpful in reducing experiments during new investigations, they have not been yet used for product and process development or for efficient control of fluid beds during coating operations. This is due to their complexity as shown by their equations. Most of the time they are derived from mathematical considerations and a few assumptions followed by adjustment of their parameters. The main drawbacks of this traditional modelling method are the lack of information about interaction with other components, the particle trajectory (Matthew, Morgan, & Littman, 1988) and the limited understanding of variable effects. So, there are two possible and complementary approaches, today, to go deeper into the understanding and modelling of a coating fluid bed.

3.2.4.3. First approach: the development and use of in-line measurement to collect process data. From the three possible methods (off-, on- and in line) for obtaining important process characteristics (particle trajectory, velocity and flux), on- and in-line measurement are used for modelling and system automation (Mörl & Drechsler, 2000), though on-line systems often suffer from sampling problems. This approach requires high-tech sensors and probes (optic fibres, positron or fast camera, laser, acoustic, etc.) and is very expensive. The actual results show that some techniques are available for coarse particles (tablets and pellets) such as optic fibres with high-speed cameras (Jones, 2000) or positron camera (Seville, 2000). A lot of improvements are expected in this field for application to fine particle coating (Maronga & Wnukowski, 1997).

3.2.4.4. Second approach: computation. With the development of powerful computer and software, the use of computation techniques is very applicable today for process and product development. The most used computation techniques are the experimental design (Kasa, 2000) and neural networks (Schmidli, 2000). If available time and money are exhausted by these methods, their successfulness strongly depends on the accuracy of data provided by the first method and the number of experiments.

The tendency today is to derive simple models that can be used for process control. The objective is to start-up and operate automatically the fluid bed just by entering data concerning particles and coating material properties. Just to illustrate this fact, there is almost no batch fluid bed coater running automatically. This may be one of the reasons why the batch fluid bed is still expensive for application to foods.

4. Batch to continuous coating: the problem

4.1. Brake on continuous coating application in pharmaceutical industries

During the two last decades, in the pharmaceutical industries, a compromise was quickly found between the disadvantage of the batch concept (low production rate and the scale-up problems) and the damage that can be caused by rejecting a continuous line production. Continuous fluid bed granulation processes and equipment were rarely used in the pharmaceutical industries to the advantage of the batch process. The main reason of this situation is that pharmaceutical industries are very familiar with batch processes. This batch concept offers the advantage of minimising losses after process problems such as contamination or formulation errors: low quantity with high quality assurance as a batch can be accepted or rejected and the high cost of the batch coating process being covered by the high value of pharmaceutical product.

Today, with more and more competition between these companies continuous processes are becoming more and more important. For example, at present, when contamination or process difficulties are not a problem, these industries use the continuous process, whether for granule drying or mechanical production of pellets.

4.2. The necessity of continuous fluid bed coating in food industries

Compared to pharmaceutical industries, the situation in food industries, where large quantities and low prices are required, is more critical. Table 1 presents a comparison of the characteristics of a batch fluid bed and a continuous one. It appears from that table that a continuous process is the only alternative to allow application (low price) of fluid bed coating to food powders. The use of a continuous process in this field is widely sought 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 latter is only suitable for product that can be tumbled.

The necessity to coat fine particles was recognised since the seventies with the emergence of some new methods for continuous encapsulation currently, but the most widely used method for food particle coating is encapsulation by spray drying. It consists in the formation of an emulsion or suspension of coating and core material followed by atomisation of the emulsion in a hot air drying chamber. Moisture from the droplets evaporates and the remaining solids of the coating material entrap the core. Spray chilling, spray cooling and prilling are variants of this process. They are based on the same principle as spray drying with the difference that cold air rather than heat is used to solidify the coating material. These types of process lead to capsules called a matrix system (Fig. 1(c)) where the core material is dispersed randomly in the coating material. Parts of the coated material may be exposed to air and are not protected. The quality of the final product is very poor because it is a mix of free spray dried coating polymer and core with encapsulated spray dried core and some free core crystal. Another disadvantage of this process is its limitation to small particle sizes that can be dispersed and sprayed (less than 100 μm) (Jacson & Lee, 1991).

During the last decade, the uses of continuous fluid beds were effective, not for coating but for all operation based on the high agitation application: drying, mixing, cooling, cooking, granulation and agglomeration etc (Ormos, 1994; Rümpler, 1999). The following continuous fluid beds for coating are the result of recent research works.

5. Continuous fluid bed coating

5.1. Single bed continuous fluid bed

The first idea was to use the classical single bed as a monocellular continuous fluid bed. This has the advantage of operating exactly as with a batch fluid bed granulator, the kinetics and mechanism of growth in batch and continuous fluidised bed being almost the same (Waldie, Wilkinson, & Zachra, 1987). The difference is that in the continuous fluid bed, particles with a pre-defined size are automatically discharged via the discharge pipe located at the centre of the processing chamber (Fig. 8). The air velocity within the discharge pipe can be accurately controlled to achieve the desired classification (gravity classification) of the product. The dust and crushed oversized particles following classification of the particles are recycled as seeds into the

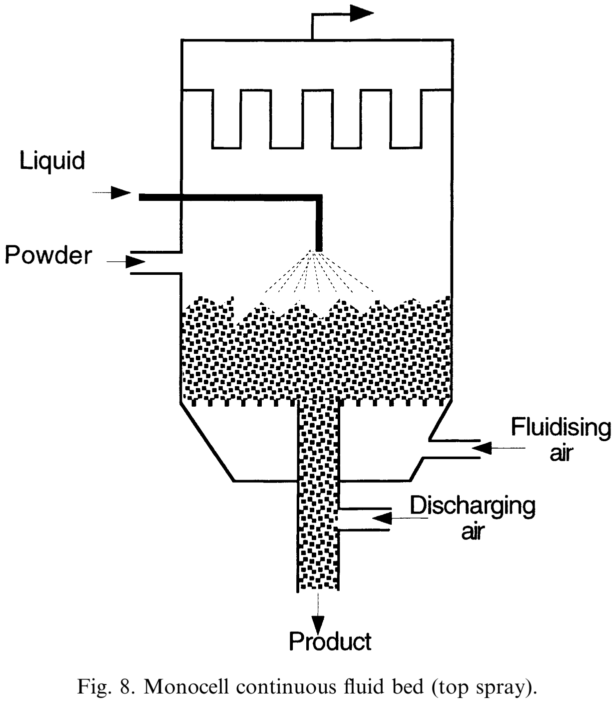

Fig. 8. Monocell continuous fluid bed (top spray).

fluidised bed. There are a variety of continuous single bed fluid bed reactors with some modifications or accessories to improve the capsules properties: shape, density (Ormos, 1994).

The advantages of this technique are high output, compact design, pre-determinable grain size, dust free and narrow particle size distribution (because of the discharging pipe classification) and low energy consumption.

The main drawback 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. Particular attention must be focussed on the processing parameters, specifically the liquid spray rate, the drying capacity and the chemical properties of different components.

The horizontal fluid bed was designed to overcome these drawbacks.

5.2. Horizontal continuous fluid bed

5.2.1. The real horizontal fluid bed for coating

The real horizontal fluid bed (Fig. 9) refers to one fluid bed with no obstacles in the system. Powder is admitted to the fluidising chamber at one end from which it moves slowly during the desired process until it gets out at the other end. This type of fluid beds exists and is actually used in food industries for many purposes. They are in general vibrating fluid beds with a conveying belt and have been designed since the seventies with a reasonable length. They were especially developed for granulation of powders after spray drying (instantizing).

The main disadvantage of the real horizontal fluids bed is their length (several metres) which is necessary to allow the required residence time for the process. This disadvantage is worsened when the process is time consuming as when coating. To illustrate this situation, here are characteristics of a real horizontal fluid bed coater that has the same performance as a wurster system. These characteristics are issued from a simulation, based on experimental and calculated data (Eqs. (3),(12)–(16)) of lactose coating by Eudragit E100 in a wurster fluid bed (Table 2). It can be read from that table that, in the defined coating conditions, to coat the lactose particle with a 25 μm thickness of Eudragit polymer, 35 min are needed. Particles are recycled through the coating zone in a matter of about 13 s (t_{cycl}) corresponding to the sum of the three residence times (t_c, t_a, t_d). During the 35 min coating time (t_{coat}), they are recycled about 160 times (N) at a flow rate of 0.016 kg/s, i.e. about 60 kg/h. The cycling distance, estimated to about 0.5 m, was calculated as the perimeter of a rectangle (20 cm long and 5 cm width) which reasonably corresponds to the path covered by a particle. The average total distance covered by particles during these 160 cycles is then about 80 m (L). The average velocity of particles, calculated as the total distance, L, divided by the coating time (t_{coat}), is about 0.04 m/s.

So, if this coating has to be carried on in a horizontal fluid bed and at 60 kg/h, this fluid bed must be theoretically 80 m long. In addition, a spray nozzle must be placed every 0.5 m (i.e. 160 nozzles) and the average particle velocity must be about 0.04 m/s. It is quite understandable that such installation could not be credible, especially because there is no guarantee of having the same product quality. The challenge that was defined was then to reduce this length while keeping the same product quality.

5.2.2. Multicell continuous fluid beds for coating

By the end of the nineties, important fluid bed manufacturers decided to reduce that theoretical length by increasing the residence time in the fluidised chamber.

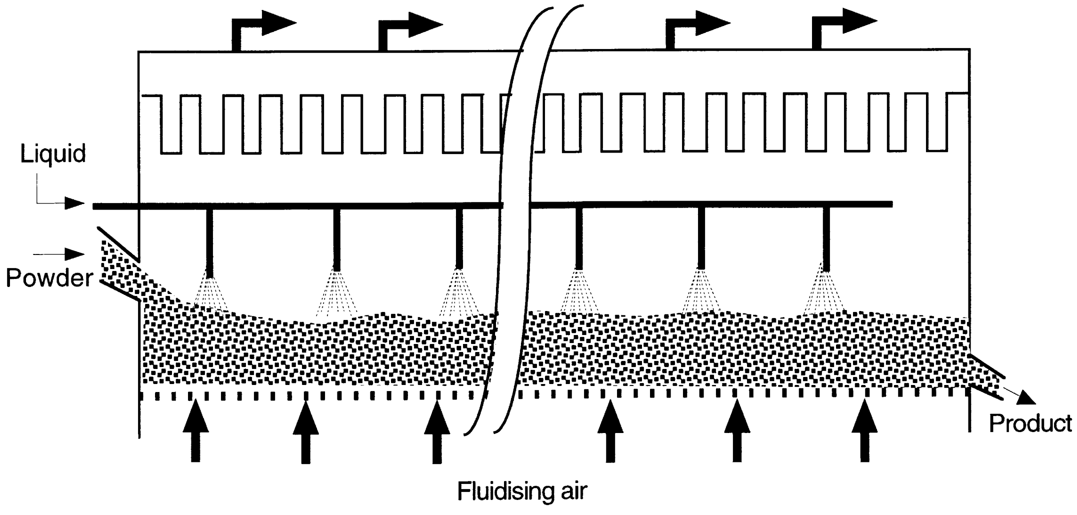

Fig. 9. A real horizontal fluid bed (top spray and continuous).

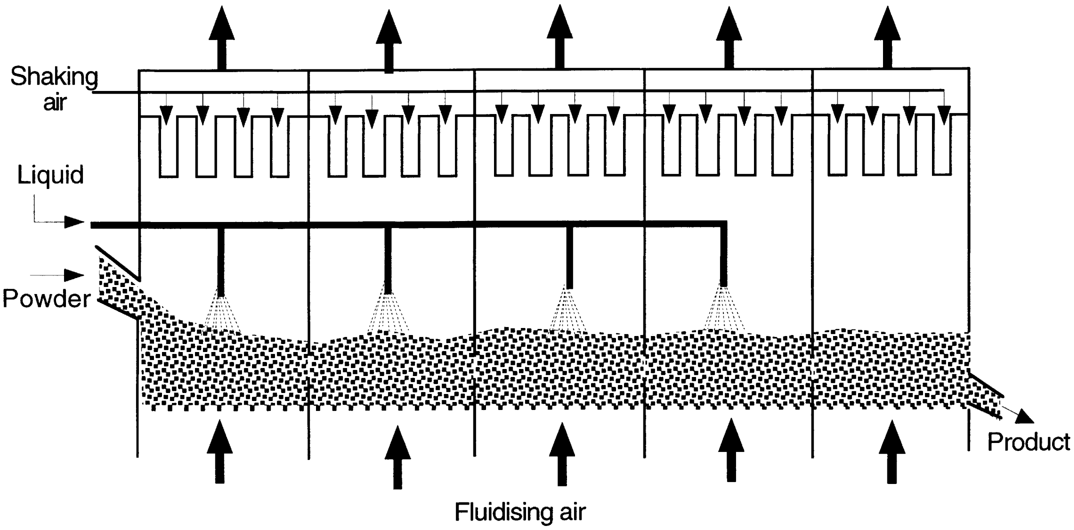

Fig. 10. The multicell continuous fluid bed.

This is possible by a judicious exploitation of fluid bed properties (Fig. 4). Manufacturers finally came out with a multicell fluid bed coater, which is a horizontal top spray fluid bed divided into four or five compartments connected by regulating flaps (Fig. 10). This apparatus, which is as versatile as the previous horizontal granulator, allows better coating. But it leads to imperfect capsules where the coating material does not recover the total surface of the core material (Fig. 1(d)), limiting their application to, for example, taste masking.

Another weakness of the multicell is that it is not appropriate for powders with a large particle size distribution, since the trajectory of particles in such fluid bed strongly depends to their weights and sizes. The use of a classifier in the discharging pipe can be a solution but it leads to a monodispersed final product (Rümpler, 1999). Indeed by enabling too small particles to return into the fluid bed chamber, these last have only two possibilities of passing through:

- stick to coarse particles (this is agglomeration-not desired during coating);
- stay longer in the fluid bed chamber, receiving layer and layer of the coating material until they reach the targeted size after many cycles. The probability of this second possibility is to low.

Finally, in both cases, the use of a classifier results in a wide residence time distribution and monodispersed granular materials. This last property is sometimes in great demand.

Another multicell fluid bed is the quasi-continuous production line, also a top spray. It consists in several mini-batches connected each other with a transport, dosage and a classification system (Fig. 11). It can be described as a train of mini batches passing like parcels the compartments of dry mixing, granulation and drying. Leuenberger (2000) developed it, in collaboration with a manufacturer, to combine advantages of batch and continuous processes in pharmaceutical industries. Leuenberger's pioneering investigations are probably the most reliable works that reconcile the two constraints present in the pharmaceutical process. There is no information about coating with this system but it can be already noted that this is an expensive installation.

5.2.3. Guidelines for a continuous fluidised bed for food powder coating

The following proposals are basically design aspects and must be tested and validated before any introduction because the design of industrial fluid beds is still completed on the basis of pilot plant testing and on-site operational experience. This empirical knowledge is indispensable for the design of different critical parts of an ideal continuous fluid bed.

Food powders, except in some specific cases, are produced with a wide particle size distribution. Coating of such material is very difficult because the behaviour of the particles in the fluid bed is far to be homogeneous. Increasing the residence time and the use of classifiers at the outlet are not sufficient. Indeed, the key point to improve the coating quality here is increasing the probability of collisions between droplets and particles. So, the following discussion will focus on the ideal horizontal continuous fluid bed for powder coating. The idea is to sketch the scheme of a horizontal fluid bed and to underline all aspects that can improve the coating quality. Obviously those problems are all related to two distributions (particle size and residence time).

5.2.3.1. Powder feeding. The powder to be coated is stored in a hopper, which allows mass flow, the best type

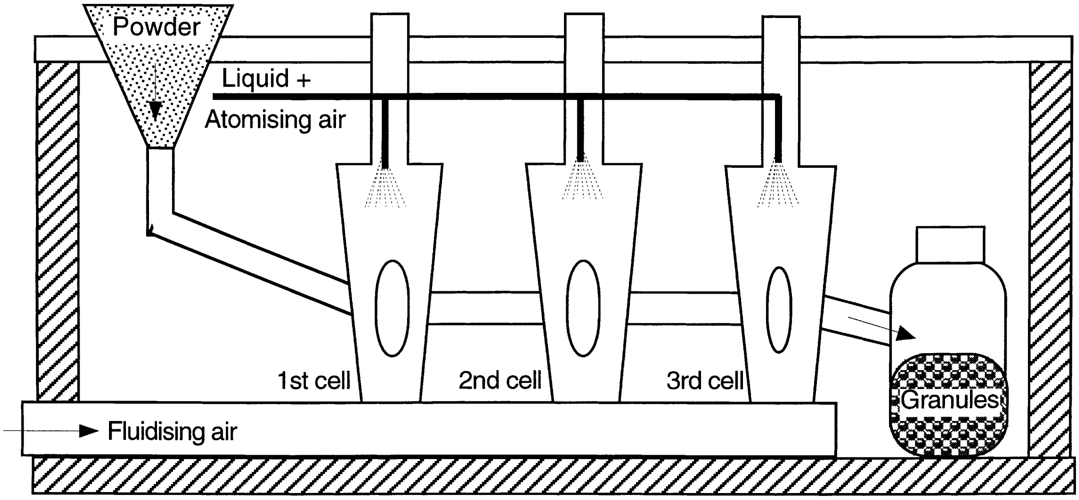

Fig. 11. Scheme of a quasi-continuous fluid bed (multicell).

of flow for food powders (no channelling, segregation and dead area). This can be achieved by designing the hopper (wall angle and aperture diameter) according to the shearing testing method, which is a mechanical approach, developed by Jenike, to test the flowability of powder (Teunou, 1997). From this hopper powder is admitted into the fluid bed chamber by a feeder. One of the important characteristics of this feeder is to provide a variable feed rate. Indeed the feed rate and the discharge rate are linked in order to define the flow rate of the continuous process and determine the mean residence time. A screw feeder unit (stepped pitch screw or decreasing shaft diameter) is the most suitable in such a powder handling situation but it is not certain that it can fulfil another important characteristic of the required feed system which is to prevent the fluidising air to escape from the fluidising chamber. Controllable rotary valves (Fig. 12) seems to be the suitable candidates in this case because they can allow feeding to pressure areas with pressure differentials of more than 1.5 bars, up to 3.5 bars (Schulze, 1994) but they can create some dead area in the hopper. So, experiments may be carried out to find out the best design of such valves without a dead zone or the efficiency of a combination of a screw feeder with rotary valves.

5.2.3.2. The fluidised bed chamber. There is almost no literature about the importance of the continuous fluid bed chamber design, probably because most of the time researchers were dealing with monocell fluid beds which

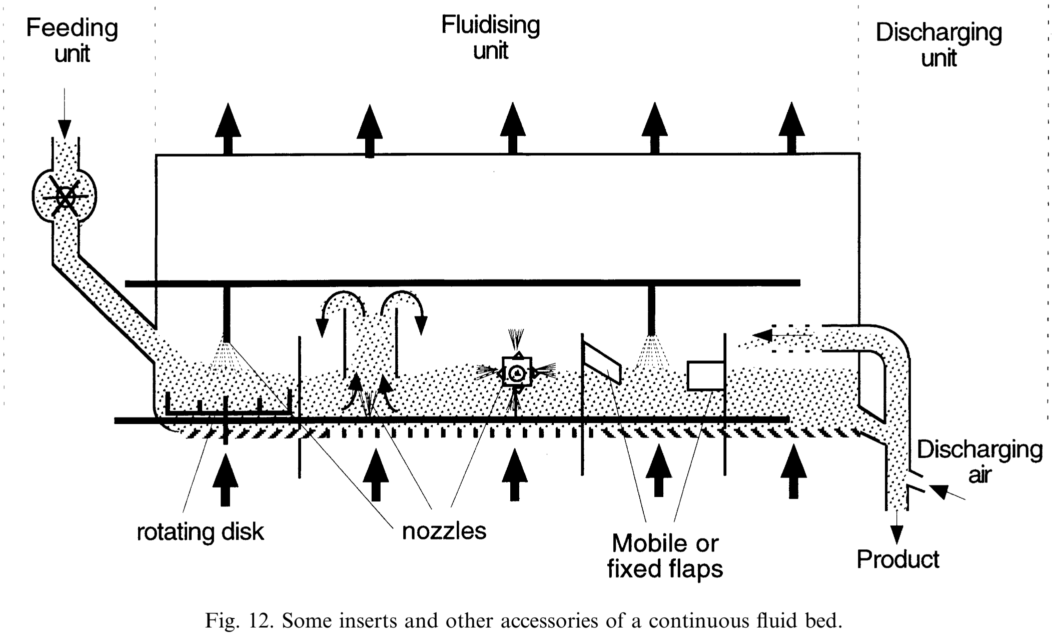

Fig. 12. Some inserts and other accessories of a continuous fluid bed.

are spherical. This shape is the ideal shape for fluid beds because it offers the best air circulation with little dead area. It is also known that corners in a rectangular shape bed are potential dead areas where agglomeration can take place during the coating process. That is one the reason why the Leunberger's quasi-continuous multicell (with individual ideal cells connected by pipes) is better than the normal multicell (Fig. 10). An evident solution is to build fluid beds with round corners that will favour the sphericity and the motion of particles (Fig. 12).

5.2.3.3. Particle motion. Greater attention must be given to the components of the fluidised bed because of their effect on particle trajectory. One of them is the air distributor plate which has a vital role in influencing product movement in the fluid bed, dead area and discharging. It is well known that with a fixed air velocity, fluidising a powder with a wide particle size distribution is very difficult to achieve (Masters, 1993). They are a few approaches to fluidise such materials:

- Vibrating the fluid bed enhances the quality of the fluidisation and allows a gentle transportation of particles (coarse and fine). But this must be tested because vibration may not be recommended during powder coating since it damages seriously the quality of the final capsules.
- A well designed air plate distributor is an alternative to improve particle transportation during particle coating in the fluid bed and consequently the particle motion in the bed. The fluid bed designer can choose among a large variety of plates today, each with its advantages and drawbacks, e.g. perforated, gill, flex, non-sifting flex plates (Masters, 1993).
- Inserts such as chicanes, cylinders as in the wurster fluid bed, regulating flaps (Fig. 12), and other type of barriers are useful tools that could help (by their position and inclination) in orientating particles motion in the system as desired.

5.2.3.4. Spray nozzle. Till now, all continuous fluid beds are top spray reactors, mainly because this configuration is easy to handle (top position, no interaction with the plate or air flow). A large variety of spray nozzles is available today: centrifugal, pneumatic, ultrasonic, rotating disk, ..., delivering droplets with different sizes and size distributions (Liu & Lister, 1993). Some are designed for high jet penetration (Bayvel & Orzechowski, 1993), others for high speed spray production. As has been stated in the paragraph ("Optimisation by design improvement"), it is not necessary to insist on a revolution in spray nozzle design. The most important thing here is to draw the attention of the reader on the fact that the types, the positions of the nozzles (top, bottom or tangential) and their number (Fig. 12) are design aspects that can have a large impact on the coating quality (Hall & Pondell, 1980). The type, their number and position must be chosen in accordance with particle motion in the fluid bed in order to favour homogeneous collisions between droplets and particles, while increasing the drying time and reducing agglomeration potential.

The pressure of the atomizing air in the nozzle is a critical parameter affecting the quality of the granules. Indeed, this pressure affects inversely the size of the droplets and consequently the granule's growth and their properties (different densities, percentage of large granules, friability and flowability). It has been reported by Pinto (2000) that there is an optimum pressure that promotes the production of granules with the best properties.

5.2.4. Granules or capsules discharging

The discharging device is a critical point of a continuous fluid bed because it can help to monitor the flow or increase the residence time. In addition it can be the control for separation between non-coated and coated particles, but this separation is not easy. Indeed, continuous fluid bed processes present a real problem of powder handling and processing which consists in finding effective criteria to separate non-homogeneous particles at the reactor outlet, in other words, how particles could be recognised as coated or non-coated materials. As was mentioned previously, the use of air classifiers with a backward surge of fine particles (Fig. 12) leads to monodispersed capsules. This system is efficient if the targeted size or weight is larger than the maximum size or weight of particles to be coated, the consequence being the very high residence time for fine particles.

5.2.4.1. Modelling. There is no doubt about the usefulness of modelling in solving such complex and interpenetrating problems. Note that modelling problems associated with continuous fluid bed are almost the same as in a batch fluid bed. In another word, its efficiency will depend on the accurate measurement of particle trajectory, concentration, flux, velocities and residence time in different zones of the fluid bed.

6. Conclusion

Several processes and types of equipment are available for the production of coated food powders. Their choice, as was mentioned earlier, depends on the objectives of the coating process. In batch, they can all be used as granulators or coaters with more or less efficiency and quality product. The use of more sophisticated tools has brought and will continue to bring understanding of the granulation and coating process. This will enable the generation of suitable models prior to automation of these processes.

The most important thing that appears through this review is the fact that all problems associated with a continuous fluid bed for coating are pointed out, and that only a general solution resulting from a combination of all improvements (including the better understanding of the process) can give a better result. The success of the continuous process depends on the degree of technical solutions that will be brought to the above problems. The challenge now is to carry on a general investigation in order to come out with a continuous fluid bed coater (with rationalised technical characteristics) whose price will be cheap enough for not masking the advantage of the production cost.

Acknowledgements

We thank Klaus Eichler and Thierry Magnet for providing some useful data and information used in this review.

References

Alden, M., Torkington, P., & Strutt, A. C. R. (1987). Control and Instrumentation of a fluidised-bed drier using the temperarture-difference technique. I. Development of a working model. *Powder Technology, 54*, 15–25.

Allais, I. (1997). Transferts thermiques au cours de la réfrigération avec brumisation d'un empilement de denrées alimentaries. Thése de doctorat ENSIA, 187 p.

Arshady, R. (1993). Microcapsulation for food. *Journal of Microencapsulation, 4*, 413–435.

Bayvel, L., & Orzechowski, Z. (1993). *Liquid atomization* (p. 462). Norinan Chigier, Bristol: Taylor and Francis.

Becher, R. D., & Schlünder, E. U. (1997). Fluidised bed granulation the – importance of a drying zone for the particle growth mechanism. *Chemical Engineering and Processing, 37*, 1–6.

Briant, J. (1989). *Phénomènes d'interface - agent de surface - principe et mode d'action* (p. 340). Paris: Technip.

Chessé, C. (1999). In Les poudres s'activent, Dossier, Process, 1155, Decembre.

Chulia, D. (1994). Powder technology and Phannaceutical processes. In D. Chulia, & M. P. Y. Deleuil (Eds.), *Handbook of powder technology* (Vol. 9) (pp. 115–163).

Dewettinck, K., & Huyghebaert, A. (1999). Fluidised bed coating in food technology. *Trends in Food Science and Technology, 10*, 163–168.

Dewettinck, K., Visscher, A., Deroo, L., & Huyghebaert, A. (1999). Modelling the steady stae thermodynamic operation point of top-spray fluidised bed. *Journal of Food Engineering, 39*, 131–143.

Dezarn, T. J. (1995). Food ingredient encapsulation. In S. J. Plach (Ed.), *ACS synposium series, Washinghon DC* (pp. 74–86).

Diego, L. F., Gayan, P., & Adanez, J. (1995). Modelling of the flow structure in circulating fluidised beds. *Powder Technology, 85*, 19–27.

Dumon, R. (1981). *Les applications industrielles des lits fluidisés*. Paris: Masson.

Filkova, I., & Munjundar, A. S. (1995). Industrial spray drying systems. In A. S. Munjundar (Ed.), *Handbook of industrial drying* (Vol. 1) (pp. 263–307). New York: Marcel Dekker.

Fyhr, C., & Kemp, C. (1999). Mathematical modelling of batcht and continuous well-mixed fluidised bed dryers. *Chemical Engineering and Processing, 38*, 11–18.

Geankoplis, C. J. (1993). *Transport processes and unit operations* (3rd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Geldart, D. (1986). Single particles, fixed and quiescent beds. In D. Geldart (Ed.), *Gas fluidisation technology*. Chichester, UK: Wiley.

Guilbert, S., Gontard, N., & Gorris, L. G. M. (1996). Prolongation of the shelf-life of perishable food products using biodégradable films and coatings. *Lebensmittel-Wissenschaft-Technologie, 29*, 10–17.

Guignon, B., Duquenoy, A., Dumoulin, E. (2000). Modelling of coating of solid particles in fluid bed process. *IDS 2000-12th international drying symposium*.

Hall, H. S., & Pondell, R. E. (1980). The Wurster process. *Controlled release technologies: Methods, theory and applications* (Vol. 2(7)) (pp. 133–154). A.F Kydomiens, FL: CRC Press.

Härkönen, H., Koskinen, M., Linko, P., Siika-aho, M., & Poutanen, K. (1993). Granulation of enzyme powders in a fluidiszd bed spray granulator. *Lebensmittel Wissenchaft und Technologie, 26*, 235–241.

Jacson, L. S., & Lee, K. (1991). Microencapsulation in food Industry. *Lebensmittel-Wissenschaft-Technologie, 24*, 289–297.

Janovsky, C. (1993). Encapsulated ingrédients for the baking industry. *Cereal Foods World, 38*(2), 85–87.

Jones, D. M. (1994). Air suspension coating for multiparticulates. *Drug Development and Industrial Pharmacy, 20*(20), 3175–3206.

Jones, D. M. (2000). Use of fiber optics and high speed photography to characterise the wurster air suspension process. In Glatt (Ed.), *Proceedings of the 10th international Glatt symposium on process technology, Prague, October12–13*.

Kasa, P., Jr. (2000). Experimental design for product development. In Glatt (Ed.), *Proceedings of the 10th international Glatt symposium on process technology, Prague, October12–13*.

Kunii, D., & Levenspiel, O. (1993). *Fluidization engineering* (2nd ed.., p. 491). Stoneham: Butterworth/Heinemann.

Kester, J. J., & Fennema, O. R. (1986). Edible films and coatings: a review. *Food Technology, 47-59*.

Kusharski, J., & Kmiec, A. (1983). Hydrodynamics, heat and mass transfer diring coating of tablets in a spouted bed. *The Canadian Journal of Chemical Engineering, 61*, 435–439.

Leuenberger, H. (2000). Pseudo-continuous fluid bed processing: the glatt multi cell concept. In Glatt (Ed.), *Proceedings of the 10th international Glatt symposium on process technology, Prague, October12–13*.

Link, K. C., & Schlunder, E. U. (1997). Fluidized bed spray granulation. Investigation of the coating process on a single sphere. *Chemical Engineering and Processing, 36*, 443–457.

Liu, L. X., & Lister, J. D. (1993). Spouted bed seed coating: the effect of process variables on maximum coating rate and elutration. *Powder Technology, 74*, 215–230.

Maronga, S. J., & Wnukowski, P. (1997). Establishing temperature and humidity profiles in fluidised bed particulate coating. *Powder Technology, 94*, 181–185.

Masters, K. (1979). *Spray drying* (p. 702). London: Leonard Hill Books.

Masters, K. (1988). Drying of droplets/sprays. In *Spray drying handbook* (pp. 298–342). New York: Longman/Wiley.

Masters, K. (1993). Importance of proper design of the air distributor plates in a fluidized bed system. *AICHE Symposium Series, 89*(297), 118–126.

Matthew, M. C., Morgan, M. H., & Littman, H. (1988). *The Canadian Journal of Chemical Engineering, 66*, 908–918.

Mörl, L., Drechsler, J. (2000). In-process particle characterisation in fluid bed applications-preparing for process control. Otto von Guericke Universitat, Lasentec.

Ormos, Z. D. (1994). Granulation and coating. In D. Chulia, M. Deleuil, & Y. Pourcelot (Eds.), *Handbook of powder technology,* *vol. 9: Powder technology and pharmaceutical processes*. Netherlands: Elsevier.

Pinto, J. F. (2000). Identification and selection of factors that most affect granule's grwth. In Glatt (Ed.), *Proceedings of the 10th international Glatt symposium on process technology, Prague, October12–13*.

Rocha, S. C. S., Taranto, O. P., & Ayub, G. E. (1995). Aerodynamics and heat transfer during coating of tablets in two-dimensional spouted bed. *The Canadian Journal of Chemical Engineering, 73*, 308–312.

Rümpler, K. (1999). Continuous fluid bed lipid coating of particles. *9th international Glatt symposium*, Weimar.

Schmidli, H. (2000). Neural networks for product and process optimisation. In Glatt (Ed.), *Proceedings of the 10th international Glatt symposium on process technology, Prague, October12–13*.

Schubert, H. (1981). Principles of agglomeration. *International Chemical Engineering, 21*(3), 363–377.

Schulze, D. (1994). Granulation and coating. In D. Chulia, M. Deleuil, & Y. Pourcelot (Eds.), *Handbook of powder technology, Vol. 9: Powder technology and pharmaceutical processes*. Netherlands: Elsevier.

Seville, J. P. K. (2000). Interparticle forces in agglomeration. In Glatt (Ed.), *Proceedings of the 10th international Glatt symposium on process technology, Prague, October12–13*.

Teunou, E. (1997). Caractérisation de l'écoulement instantané et après un temps de stockage des poudres alimentaires. Thesis, ENSIA de Massy, France.

Valenti, C. (1998). Etude d'un rocédé d'enrobage en lit fluidisé. Le procédé Wurster. Thèse, Université Henri Poincaré-Nancy I.

Waldie, B., Wilkinson, D., & Zachra, L. (1987). Kinetics and mechanism of growth in batch and continuous fluidised bed granulation. *Chemical Engineereing Science, 42*(4), 653–665.

Wan, L. S. C., Heng, P. W. S, & Chia, C. G. H. (1992). Spray drying process for microencapsulation and the effect of different coating polymers. *Drug Deveolpment and Industrial Pharmacy, 18*(9), 977–1011.

Wurster, D. E. (1950). Means for applying Coatings to tablets or like. *Journal of the American Pharmaceutical Association, 48*(8), 451.

Yvon, J., Thomas, F., Villieras, F. et, & Michot, L. J. (1994). Surface-activity of water. In D. Chulia, M. Deleuil, & Y. Pourcelot (Eds.), *Handbook of powder technology, Vol 9: Powder technology and pharmaceutical processes*. Netherlands: Elsevier.