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Optimising product quality and process control for powdered dairy products

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16.1 Introduction: evaporation and drying processes

Fresh milk and dairy products have a high nutritional value, but as the products as such have a limited shelf-life they should be processed in order to become microbiologically stable. One of the widely used techniques for this is reducing the water content, and thereby the water activity, by concentration and drying. Another advantage of these water-removing techniques is the decrease in costs for storage and transportation by reduction of the product volume. The disadvantage, however, is that the energy consumption for drying is high; no other process in the dairy industry has such a high energy demand per tonne of finished product. This is due to the fact that approximately 90% of the milk is water, and practically all that water has to be removed by heat. The removal of water usually takes place in two stages. The first stage is concentration by vacuum evaporation and the second stage is drying; 90% of the water is removed in the evaporator and only 9–10% in the spray dryer when calculating the amount of water removal per dry mass. However, the energy required per kg water evaporated in the dryer is about 15 times the energy required per kg water removed in the evaporator (see also Table 16.1).

Besides the processing of the milk products, an important criterion for preservation by concentration and drying is the quality of the (recombined) product. Modern technologies are focused on minimising the loss of nutritive value, improving microbiological quality and improving the rehydration properties of the milk powder. Nowadays, optimal design by using predictive process and product models and advanced automation are the ingredients for producing high-quality products for the food market (De Jong and Verdurmen, 2001).

Table 16.1 Typical figures for the conversion from milk to milk powder

Product	Milk	Concentrated milk	Milk powder
Total solids (%)	10	50	96
kg water per kg total solids	11.1	1	0.04
Specific energy use for conversion (MJ/kg water evaporation)	0.3	4.4	

16.1.1 Evaporation

In the dairy industry falling-film evaporators are commonly used and have practically replaced all other types. Falling-film evaporators operate as thin film evaporators, resulting in short retention times and gentle heat treatment. The heat exchange surface consists of a bundle of vertical tubes. In Fig. 16.1 a basic scheme is shown of a modern falling-film evaporator plant for concentration of milk products. In practice a large number of different evaporator configurations are used in the industry. For example, the number of evaporator effects (tube bundles) varies from one to seven. The actual configuration depends on the desired properties of the concentrate and the state of the art at the time of installation of the evaporation plant.

In order to obtain a high thermal efficiency in a number of cases the products are heated first in spiral tubes placed in the condenser and the evaporator effects. Before the product enters the evaporator effects, it is preheated to a temperature above the boiling temperature of the first effect. In general, the whole preheating trajectory has a great impact on the properties and quality of the concentrate and powder. To meet some quality standards, it can be necessary to use a direct heater (e.g. steam injection, steam infusion) to apply a short-time high-temperature treatment.

The product entering an effect of the falling-film evaporator is distributed (e.g. by distribution plate, see Fig. 16.2) over the bundle of evaporation tubes. The liquid is 'falling' as a film through the inner side of the tube. On the outer side of the evaporator tubes steam is condensing. The water evaporation, which usually takes place below 70–80ºC, is based on the physical law that the boiling point of a liquid is lowered when the liquid is exposed to a pressure below atmospheric pressure (Bouman *et al.*, 1993). The vapour is separated from the product in a separator placed at the base of the effect and is used as the heating medium for the next effect. From the last effect, the vapour goes to the condenser. This can be an open condenser in which the product is condensed by direct contact with a water spray, but in modern evaporators the vapour is condensed using an indirect heat exchanger in order to reduce water usage. The boiling temperatures in the effects vary from 70–80ºC in the first effect to 40–50ºC in the last effect.

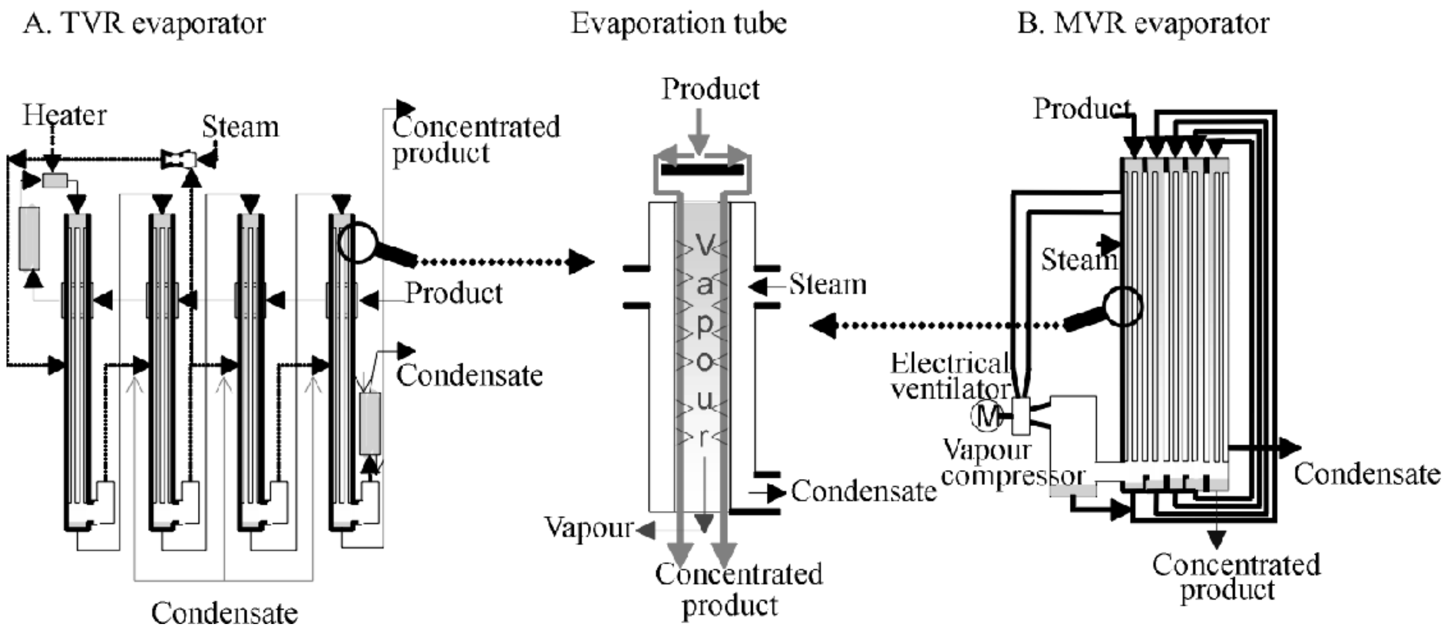

Fig. 16.1 Schematic representation of industrial configurations of falling-film evaporators.

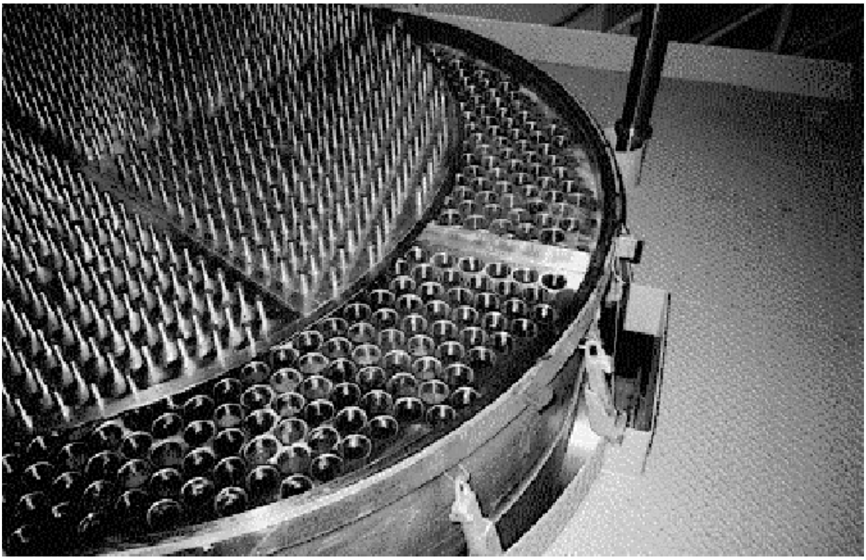

Fig. 16.2 Example of an industrial liquid distribution device (courtesy of Carlisle Processing Systems – Friesland).

Generally, the heat transfer is given by:

$$Q = kA(T_v - T_p) \qquad 16.1$$

where

$$\frac{1}{k} = \frac{1}{\alpha_p} + \frac{\delta_w}{\lambda_w} + \frac{1}{\alpha_v} \qquad 16.2$$

and k is the overall heat transfer coefficient (W m^{-2} s^{-1}), A the amount of heat transfer area (m^2), T_v the vapour or steam temperature (ºC), T_p the product temperature (ºC), α_p the heat transfer coefficient of the product side, α_v the heat transfer coefficient of the vapour side, δ_w the wall thickness of the evaporator tube (m), and λ_w its thermal conductivity (W m^{-2} s^{-1}). Based on a large set of experimental and industrial data, Bouman *et al.* (1993) found that the heat transfer coefficient at the product side can be described by the following empirical equation:

$$\alpha_p = c_1 \cdot q^{c_2} \cdot m^{c_3} \cdot \eta_p^{c_4} \qquad 16.3$$

where q is the heat flux (W m^{-2}), m the wetting rate (kg m^{-1} s^{-1}), η_p the viscosity of the product (Pa s), and c_1–c_4 are constants.

It is well known that by increasing the number of vacuum units (effects) the energy consumption decreases. For example, in the case of four effects 1 kg of steam results in 3–4 kg of water evaporation (Písecký, 1997). Recompression of a part of the vapours (TVR) will also decrease the steam consumption. In the thermocompressor steam is introduced through a nozzle creating a steam jet in the mixing chamber, whereby vapour from the separator is sucked into the mixing chamber.

An indication of the energy consumption of a multi-stage falling-film evaporator with thermal vapour recompression can be calculated from:

$$E = \frac{\left(1 - \frac{\mathrm{DS_{in}}}{\mathrm{DS_{out}}}\right)\phi_{\mathrm{in}} h_{\mathrm{v}}}{N_{\mathrm{effects}} + N_{\mathrm{effects,TVR}}} \qquad 16.4$$

where E is the energy consumption (J kg^{-1} raw material), DS the dry solids content of the raw material and the product (%), ϕ_{in} the flow of the raw material, h_{v} the heat evaporation (J kg^{-1}), N_{effects} the total number of effects, and $N_{\mathrm{effects.TVR}}$ the number of effects with thermal vapour recompression.

A more energy-efficient recompression method is the application of mechanical vapour recompression (MVR). In contrast to TVR, all the vapour is recompressed. Normally, the MVR evaporator consists of only one or two effects and the boiling temperature can be chosen depending on the desired product properties. Apart from the steam used for start-up, an MVR evaporator requires no steam and no cooling water. Modern MVR evaporators use a heavy-duty fan instead of a relatively complex compressor. This has resulted in diminishing investment costs and nowadays most of the new evaporators use MVR. In Table 16.2 compares the energy consumption of TVR evaporators and the latest generation of MVR evaporators (Vissers *et al.*, 2002).

Depending on the desired product properties the concentrate from the last effect can be homogenised, heat-treated and/or crystallised. When the concentrated product is used for powder production the product is transported to a balance tank.

16.1.2 Drying

In the dairy industry drying of concentrate into powder is mainly done by spray drying. Spray drying is a relatively gentle drying process that has replaced the cheaper but also the more product-denaturing drum dryers. Moreover spray drying makes it possible to manufacture powder qualities for different applications and quality standards.

Table 16.2 Comparison between the energy consumption of TVR evaporators (six effects) and the latest generation of MVR evaporators. Figures based on 30–40 tonnes water evaporation per hour

Energy consumption (m^3 natural gas equivalents per tonne water evaporation)	TVR	MVR (new generation)
Specific steam consumption	10.8	0.5
Specific electricity consumption	0.8	3.0
Total specific energy consumption	11.6	3.5

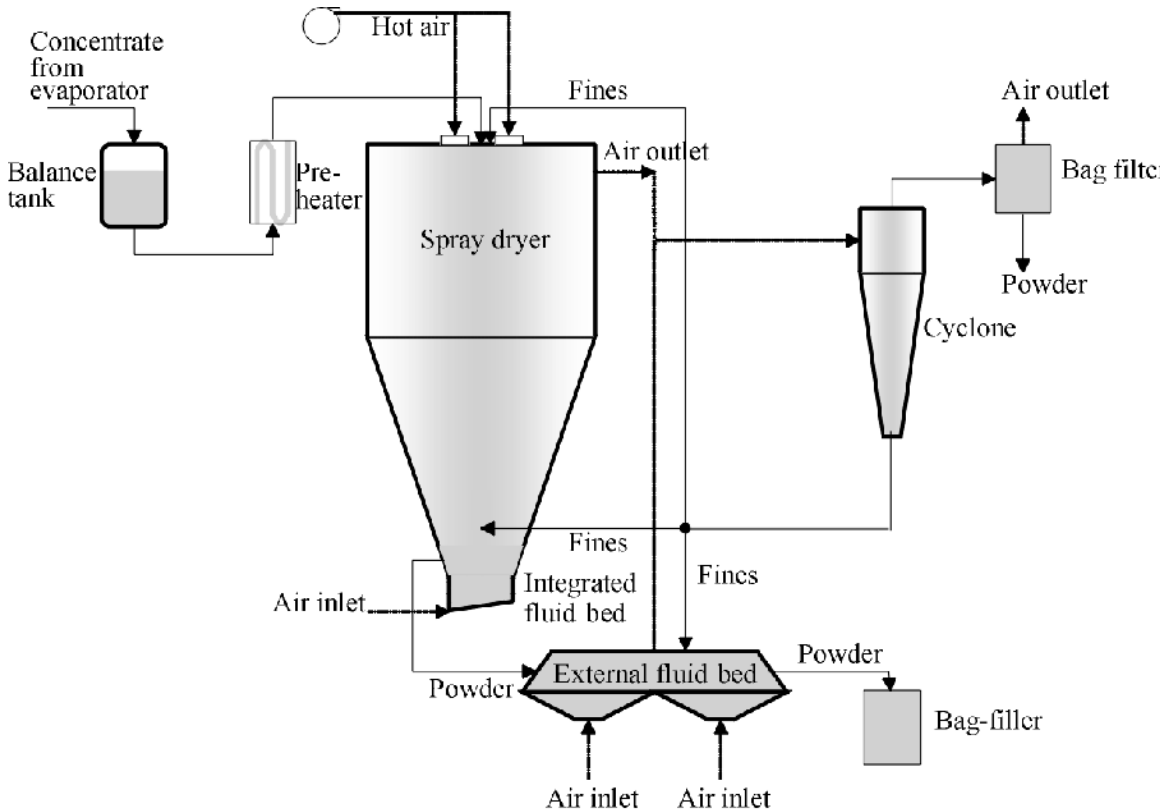

Fig. 16.3 Schematic representation of industrial configurations of spray dryers (single-, two- and three-stage).

In Fig. 16.3 the scheme of a multi-stage dryer is shown. In practice a spray dryer can consist of one, two or three stages. Multi-stage drying increases the thermal efficiency of the drying process (about 20% less energy, Filková and Mujumdar, 1995), produces agglomerated powder with good rehydration properties (see Section 16.2.2) and prevents overheating of powder particles (Písecký, 1997). In the first stage, the preheated product (<100ºC) is sprayed by atomisation into a chamber filled with circulating hot air. The inlet temperature of the air is normally 150–250ºC. By atomisation the concentrate is converted into droplets of 10–200 μm. In the industry two atomisation systems are used: stationary pressure nozzles and rotating atomisers. The droplets are flowing in the tower and adsorb heat necessary for evaporating the moisture. The moisture is removed by the hot air. Depending on the dimensions of the tower, the residence time of the powder particles is in the order of 5–30 seconds. The dried powder falls to the bottom of the dryer and is transported to the next drying stage

Fig. 16.4 The bottom of a spray chamber incorporating an internal fluid bed and an external fluid bed (courtesy of Anhydro A/S).

or to a packaging system. The exhaust air is removed through an outlet duct and passes through cyclones and filters where small powder particles (fines) are removed. The fines can be recycled to the top of the dryer or to other drying stages. The result is an agglomerated powder.

As said before, the first processing stage is done in the dryer chamber. For the next stages normally fluid-bed dryers are used, both internal in the drying chamber and external (see also Fig. 16.4). In the fluid bed a powder layer is formed of a defined height through which hot air (cooler than the tower hot air) is flowing. In certain cases the fluid bed is used to achieve some product transformations, for example lactose crystallisation in whey powder. Lecithination during drying in the external fluid bed is in some cases (e.g. whole milk powder) applied to improve instant properties. In the final part of the fluid bed the powder is cooled towards the packaging and storage temperature.

16.2 Quality criteria for dairy-based powders

Different aspects of the quality of dairy-based powders can be distinguished: microbiological quality, quality of physical properties and chemical quality.

16.2.1 Microbiological quality

The requirements for the microbiological quality of dairy-based powders depend partly on its intended use and partly on the manufacturing process. In this perspective it is of importance as to whether powder is an end-product and will be used for human consumption or whether it is an intermediate product that is subjected to heating after reconstitution (e.g. as an ingredient for other products). The reasons for milk powder to be microbiologically unacceptable or even a health risk can be of three kinds:

1. The microbiological quality of the raw materials used. For example in fresh milk, heat resistant bacteria and bacterial spores can be present that are not inactivated by the heat treatments to which the milk is subjected before and after drying (Walstra *et al.*, 1999);
2. Conditions during the various process steps before the formation of powder allow growth of some species. Especially thermophilic bacteria can grow in regenerative sections of heat exchangers and in evaporators (De Jong *et al.*, 2002a, 2002b);
3. During powder manufacture, incidental contamination can occur at many places – in the spray dryer, in the fluid beds and during packaging. This can usually be avoided by taking appropriate hygienic measures.

16.2.2 Physical powder properties

Many physical powder properties can be influenced by certain pretreatment processes, by choosing the conditions for evaporation and spray drying and by applying various post-drying treatments. The most important physical powder properties are listed below and how these properties can be influenced is briefly discussed.

Moisture content

The moisture content of a powder is often subject to (legal) product specifications defining the maximum moisture content. This is based on the fact that too high a moisture content may result in inferior shelf-life due to non-enzymatic browning (Maillard) reaction, creation of lumps and possibly microbiological problems. Too low a moisture content may in some cases result in an increased fat oxidation rate (Labuza, 1971; Van Mil and Jans, 1991). It is therefore very important to control the end moisture content of spray dried powder, not only in view of quality but also for manufacturing economics. When two- and multi-stage drying systems are used it is not just the end moisture content that must be strictly controlled; the moisture content of powder leaving the drying chamber (first stage of the drying process) is also important (Masters, 1991).

The moisture content of powder is influenced by a combination of factors involving feed properties (total solids content, temperature), atomisation conditions and most importantly the conditions of the drying air (inlet and outlet temperature of the drying chamber and fluid beds). The influence of the most important factors on the moisture content can be computed using heat and mass balances (Straatsma *et al*., 1991).

Insolubility index

When milk powders are reconstituted and centrifuged, some insoluble fraction can be observed. This is considered as a quality defect. Several methods have been developed to determine the insolubility of milk powders. The most well-defined method is the International Dairy Federation's method for the determination of the 'insolubility index' (IDF, 1988).

The mechanism by which insoluble material is formed is not yet fully understood. The current view is that the mechanism involves the unfolding of β-lactoglobulin, followed by aggregation with casein, but it appears that also other mechanisms play a role. The main factor controlling the insolubility index is the particle temperature during the drying stage when the moisture content is between 10% and 30%. Straatsma *et al*. (1999b) developed a kinetic model that predicts the insolubility index as a function of temperature and particle diameter.

Bulk density

Bulk density expresses the weight of a volume unit of powder and is expressed in kg/m^3. Bulk volume is also often used in the milk powder industry and is expressed as a volume in ml of 100 g of powder. Bulk density of dairy-based powders is a very important property from the point of view of economy, functionality and market requirements. High bulk densities save in packaging materials. Agglomeration may result in a low bulk density and is an important

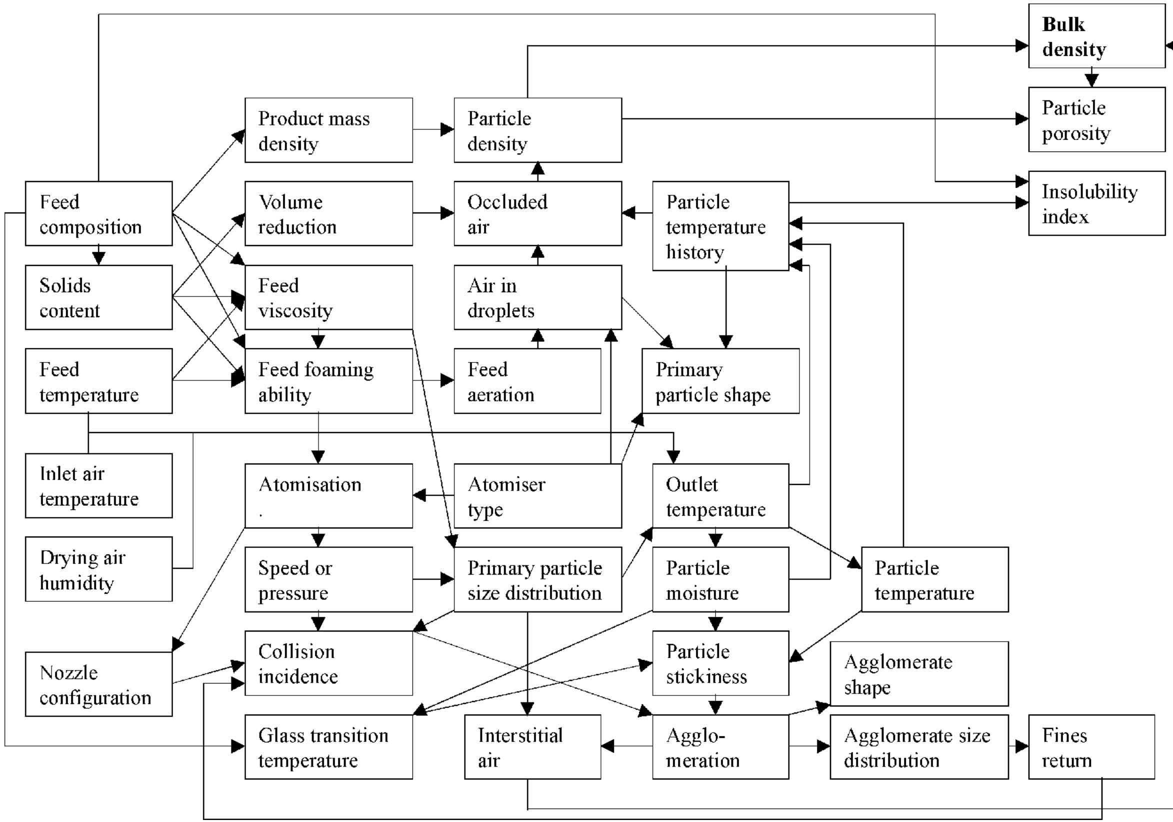

Fig. 16.5 The effect of various parameters on agglomeration and powder properties (adapted from Písecký, 1997).

factor influencing other product properties, such as flowability and instant properties. The bulk density is influenced by numerous factors as shown in Fig. 16.5. The primary factors determining bulk density are the density of the solids, the amount of air entrapped in the powder particles (occluded air) which is also reflected in the particle density and the interstitial air, i.e. the air between the particles or agglomerates (Písecký, 1997).

Agglomeration is a size enlargement process of powders, where small particles combine to form large relatively permanent masses, in which the original particles are still identifiable. In this way, the characteristics of a single particle are maintained while the bulk density is decreased by the creation of the larger agglomerates. The rehydration behaviour – the so-called instant properties – of the powder is improved because the open porous structure of the agglomerate allows water to penetrate to the particles it is originally constituted from, forcing the particle to sink. In this way, better dissolution behaviour is obtained compared to dissolving separate particles. For retention of the instant properties of the powder the mechanical strength of the agglomerate plays an important role. Low mechanical strength leads to falling apart of the agglomerate into its constituent particles when attrition forces during transport or storage are applied, thus deteriorating the instant and the flowability properties, whereas too high a mechanical strength gives a very limited dispersibility.

Agglomeration in spray dryers can be achieved by different methods. In the drying chamber agglomeration can take place within the spray of an atomiser, between sprays of various atomisers and between sprays and dry material being introduced into the drying chamber. Also agglomeration on a fluid bed, static bed or perforated belt (outside the spray chamber) is possible. Two types of agglomeration processes can be distinguished:

1. Primary agglomeration, caused by collision of primary spray particles with each other
2. Secondary agglomeration caused by collision of primary spray particles with fines.

Both processes can be either spontaneous (random unprovoked collisions) or forced. Forced primary agglomeration occurs when sprays from different nozzles collide. Forced secondary agglomeration takes place when fines from the spray dryer outlet are returned to the atomisation zone.

Several designs have been presented in order to establish the formation of ideal agglomerates by optimising the position of returning fines to the atomisation zone, by optimising the distance between the spray nozzles and the fluid bed for optimal stickiness of the particles in the fluid bed, or by adjusting the spray nozzles. In the latter case, the spray nozzles are adjusted in such a way that their spray patterns intersect at a location distant enough from the nozzles to prevent the formation of lumps, at the point where the particles are sticky enough to form agglomerates upon collision. In Fig. 16.6 a novel design is presented, where the pitch of the nozzle sticks can be changed to influence the degree of agglomeration.

Fig. 16.6 Nozzle set (three nozzle sticks and one central fines return) having the possibility to alter the pitch of the nozzles relative to the fines return. Narrow pitch (left) will lead to maximal primary and secondary agglomeration. Wide pitch and switching off fines return to the atomisation zone (right) will lead to minimal primary agglomeration and no secondary agglomeration (courtesy of Carlisle Processing Systems – Friesland, patent pending).

Flowability

Good flowability is especially important when the powder will be processed or used without mechanical handling and dosing devices. Examples of applications that require good flowability are powders to be used in coffee vending machines and milk replacers used by farmers for feeding calves. Flowability can be influenced by the following factors:

- Particle size distribution, amongst others influenced by agglomeration
- Free fat content of the powders
- Addition of free-flowing agents, e.g. silicates.

Free fat

Traditionally, the term ‘free fat’ has unfavourable associations in terms of shelf-life (oxidation), instant properties and deterioration of flowability. The term ‘free-fat’ actually means extractable fat; methods for the determination of free fat are based on contact extraction of powder by an organic solvent (e.g. carbon tetrachloride or petroleum ether). Many different methods are used for the determination of ‘free-fat’, which makes comparison difficult when the extraction method is not specified. Buma (1971) developed a physical model, dividing the extractable fat in four forms, which made the term ‘free-fat’ more comprehensible:

1. *Surface fat* present at pools or patches of fat on the powder surface.

2. *Outer layer fat*, consisting of fat globules in the surface layer of the powder particles, which can be released directly by fat solvents.
3. *Capillary fat*, consisting of fat globules inside the powder particles, which can be reached by fat solvents via capillary pores or cracks.
4. *Dissolution fat*, consisting of fat globules inside the powder particles, which can be reached by fat solvents via the holes left by dissolved fat globules in the outer particle layer or close to wide capillaries in the powder particles (also called 'second echelon fat').

Factors controlling the level of free fat are amongst others:

- Total fat content of the powder. Below approximately 26% fat, the free fat content is low but above this level it increases rapidly (Kelly *et al.*, 2002).
- Storage conditions of the powder. If lactose crystallises, due to moisture absorption from the surroundings, the free fat increases sharply (Buma, 1971).
- Total solids content of feed to dryer. Snoeren *et al.* (1983) found that increasing the viscosity of the feed resulted in a reduction of free fat.
- Homogenisation of the concentration before spray drying reduced the free fat content (De Vilder, 1979).

Instant properties

Instant properties (also called reconstitution properties) involve the ability of the powder to dissolve quickly and completely in water. This ability features a rather complicated mechanism. Each individual particle has initially to be wetted, then to sink into the liquid in order to be finally dissolved. The most important instant properties are wettability and dispersibility (IDF, 1979), but many other tests have also been developed, e.g. slowly dissolving particles, coffee test, white flecks number (IDF, 1995) and sludge. Instant properties can be improved by agglomeration, which alters the physical state of the powder to such an extent that the rates of wetting, sinking and dispersing increase. Whole milk can furthermore be 'instantised' by spraying lecithin on the agglomerated powder.

16.2.3 Chemical quality

Protein denaturation

Heat treatment of the original dairy liquid, concentrate or drying droplet can cause denaturation of serum (or whey) proteins, although the conditions during drying and concentration are rarely such as to cause extensive heat denaturation (Walstra *et al.*, 1999). This means that the main operation to adjust the required denaturation of whey proteins is the pasteurisation/heating process prior to concentration. The whey protein nitrogen (WPN) index is usually applied to classify milk powders according to the intensity of the heat treatment used in manufacturing the powder (ADMI, 1971).

The WPN index is an important quality mark in connection with the use of milk powder. If the reconstituted powder is used for cheese manufacture, the amount of denatured whey proteins should be as low as possible, i.e. low heat milk powder (WPN index $\geq$ 6) should be used. High heat milk powder (WPN index $\leq$ 1.5) is used, for example, for producing milk chocolate.

Fat oxidation

For diary products containing fat (e.g. whole milk powder) an important aspect of shelf-life is to prevent fat oxidation. Oxidation of fat will lead to the formation of degradation products, eventually leading to the development of various off-flavours. An important aspect of fat oxidation is that it is auto-catalytic. The rate of oxidation is usually slow at the beginning and increases as the reaction progresses (Labuza, 1971). The initial reaction rate is often so slow that there is an induction period at the beginning where the rate is too small to be measured. Factors controlling fat oxidation are amongst others:

- Presence of trace metals. Several metals that possess two or more valency states both decrease the induction period and increase the rate of oxidation. The metals include cobalt (Co), iron (Fe), copper (Cu), nickel (Ni) and manganese (Mn) as well as others of minor importance.
- Degree of unsaturation of fatty acids. In general it can be stated that the higher the degree of unsaturation of a fatty acid, the higher is its relative rate of oxidation. This is of special importance for dairy-based powders that contain vegetable fats or other added fats (e.g. with high amounts of polyunsaturated fatty acids).
- Oxygen concentration. Decreasing the oxygen concentration reduces the rate of fat oxidation. For this reason, oxidation sensitive dairy based powders (e.g. infant milk formulae) are packed in tins or pouches and are usually gassed with a mixture of nitrogen (N_2) and carbon dioxide (CO_2) to decrease the oxygen content below a level of 2–3%.
- Amount of anti-oxidants present in the powder. Anti-oxidants do not improve the quality of the product, but maintain it by preventing oxidation of labile lipid components. Examples of anti-oxidants are α-tocopherol, ascorbic acid and β-carotene. Free sulphydryl-groups (SH-groups) which are created in milk by high heat treatment (e.g. 30 seconds at 110ºC) also seem to have anti-oxidative properties in the powder produced from it (McCluskey *et al.*, 1997).
- Water activity or moisture content. Dehydration of foods is a good method to enhance shelf-life. However, it has been found that if food is dried to too low a moisture content (less than 2–3%), it becomes very susceptible to oxidation (Labuza, 1971). Van Mil and Jans (1991) found that the peroxide value (an oxidation product) of whole milk powder increased more rapidly at a moisture content of 2.4% than at a moisture content of 3.0%.
- Temperature. Chemical reactions proceed faster when the temperature is increased. Van Mil and Jans (1991) found that an increase in storage temperature from 20ºC to 35ºC resulted in faster fat oxidation.

16.3 Modelling quality

16.3.1 General approaches

In the dairy industry the evaporator and the dryer are controlled separately. Both the control of the evaporator and the control of the dryer are directed mainly on moisture content. To obtain a high-quality powder, it is necessary to maintain a constant dry matter content in the concentrate produced in the evaporator preceding the drying process. Changes in dry matter content in the feed to the dryer are one of the major sources of disturbance in the drying process. It is also advantageous to remove as much water as possible at the evaporation stage from an energy-saving point of view. In practice, however, due to variations that occur in dry matter content of the concentrate as a consequence of variations in feed and process variables, the set-point for this dry matter content is often lower than theoretically possible, in order to reduce the risk of too high a viscosity of the concentrate. Less variation in dry matter content of the concentrate enables a higher set-point and thus also improves the energy efficiency of the powder production process. In closely coupled production lines the production rate of the evaporator and the dryer should be balanced. Most drying processes either are controlled by the feed rate or require a constant feed rate. The concentrate flow from the evaporator should closely match this rate in order to avoid the need for large buffers.

The control of evaporators is focused mainly on a constant flow rate and dry matter content of the concentrate. Where multiple-effect falling-film evaporators are to be controlled, evaporators should be viewed as complex interacting systems. The commonly used conventional control technology, such as single-loop proportional integral and derivative controllers, will therefore perform poorly compared to multivariable controllers. Modern multivariable robust control design methods make it possible to design compensators that optimise performance objectives under uncertainty about the exact plant behaviour. Central in this approach is the process model or predictive model, partly for the transfer of the control inputs to the process outputs and partly for the process transfer from the measured disturbance (dry matter content of the feed) to the process outputs (Schaafsma *et al.*, 1997).

16.3.2 State of the art of mathematical models used for control

Black box models

Black box models such as neural network and fuzzy logic models are data-driven. In principle, physical laws are ignored. These black box models have no mechanistic basis and are very specific for the process and product trained for. Training is performed by fitting the (numerous) model constants with a huge data set of measured process and product data. In the case of fuzzy logic models it is possible to translate qualitative relations (expert knowledge) into linguistic rules. These rules avoid the model producing unrealistic numbers just outside the model training area. For example, if *temperature* is *high* then *bacterial product load* is *high.*

The main advantage of black box models is the simplicity of developing them, even for complex phenomena such as taste development. Once there is enough data, the computer tools, with some expert help, can make a model within minutes. However, even one small change in the process equipment or the composition of the raw materials means that the model must be trained again. In most cases, this makes black box models interesting for the control only of those processes and bulk products that show no variation in requirements. The only known successful applications are the control of the total solids content of the concentrate leaving evaporators and of the moisture content of bulk powders from spray dryers.

Predictive models

Traditionally (food) science is focused on white box modelling, mostly represented as a hypothesis. In principle, only models based on chemical and physical phenomena and theories can be indicated as predictive. Although no model is a real white box model, it can be stated that predictive models have a more or less white box nature. With the increasing number of models becoming available to the industry, predictive models are being introduced more and more in the research and development of new products and processes. Examples are the fouling model for the design of heat exchangers and evaporators, the contamination model for the production of high-quality food products in a factory, the prediction of the formation of taste attributes in cheeses during ripening, etc.

Reaction kinetic approach

To describe the transformation of food products during processing, good results are obtained with reaction kinetic modelling techniques. The model consists of a set of reaction rate equations based on a reaction scheme that implies a mechanistic hypothesis. Depending on the application, this set might be very simple or very complex.

During processing, raw materials behave like a complex reaction system. A large number of chemical, physical and biochemical reactions take place. Some of these transformations are important because they change those product characteristics that are easily recognised by a consumer. Examples are inactivation of enzymes, denaturation of proteins, loss of nutrients and formation of new components. In general, most of these reactions can be described by *n*th-order reactions (single or consecutive):

$$\frac{dC_1}{dt} = k_n C_1^n, \quad \frac{dC_1}{dt} = k_n C_1^n - k_m C_2^m, \quad \text{etc.} \qquad 16.5$$

A large amount of kinetic data of several food components has been collected. Models available (De Jong, 1996) are the protein fouling model, models for bacterial spores (quality related), models for vitamin breakdown, models for enzyme inactivation (shelf-life related), models for protein denaturation and aggregation, and models for protein breakdown. Examples of more complex mechanistic models are the polymerisation model for prediction of heat-induced protein denaturation and viscosity changes in milk and milk concentrates (De Jong and Van der Linden, 1998) and reaction models of the non-enzymatic browning (Maillard) process (Brands, 2002).

Reaction kinetic modelling can also be used for product–process interaction such as fouling and biofouling in preheating equipment and falling-film evaporators upstream of the spray dryer. Figures 16.7 and 16.8 show the underlying mechanisms. For example, based on this reaction mechanism De Jong *et al.* (1992) developed a predictive fouling model based on the following reaction scheme:

$$[\text{native } \beta\text{-lg}] \xrightarrow{k_1} [\text{unfolded } \beta\text{-lg}] \xrightarrow{k_2} [\text{aggregated } \beta\text{-lg}]$$

$$[\text{unfolded } \beta\text{-lg}] \xrightarrow{k_3} [\text{aggregates of milk components}] \qquad 16.6$$

$$[\text{aggregates of milk components}] \xrightarrow{k_4} [\text{deposits}]$$

where β-lg stands for β-lactoglobulin, a reactive protein in milk, and k_1–k_4 are reaction rate constants depending on temperature. The protein denaturation affects the product texture while the amount of deposits affects the heat transfer and indirectly the process economics. This model has been used for optimising dairy production plants by relating the amount of deposits to operating costs (De Jong, 1996). The same approach was applied for biofouling and resulted in a model that predicts the contamination in powders as a result of adherence and growth of bacteria upstream of the spray dryer (De Jong *et al.*, 2002a). An example of contamination prediction in equipment upstream of the spray dryer is

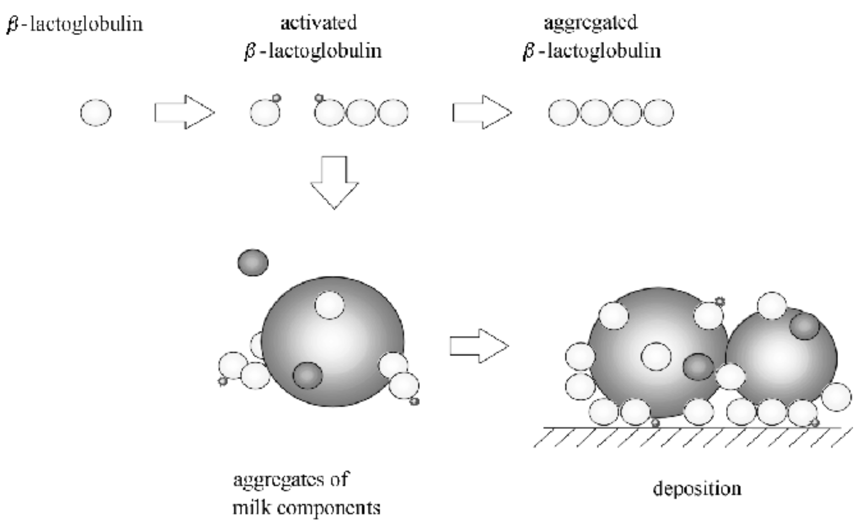

Fig. 16.7 Reaction kinetic representation of the fouling process in heating equipment.

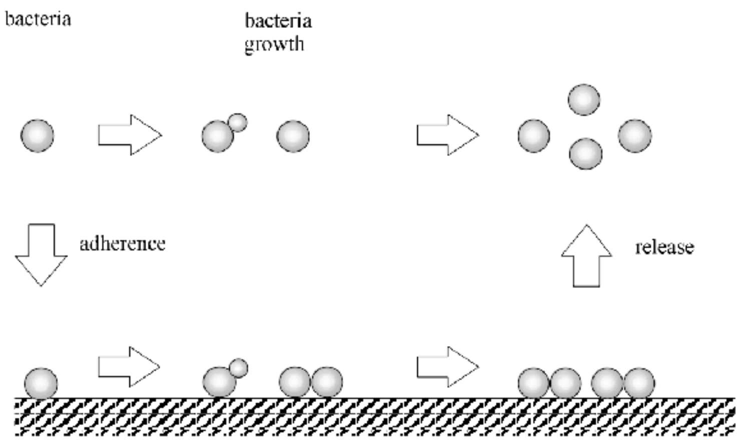

Fig. 16.8 Reaction kinetic representation of the biofouling and contamination process in heating equipment.

given in Fig. 16.9. White box models are excellent for modelling process and product development. The model constants have a physical meaning and are not dependent on process design. The main disadvantage of white box models is the time of development; however, an increasing number of white box models are becoming available.

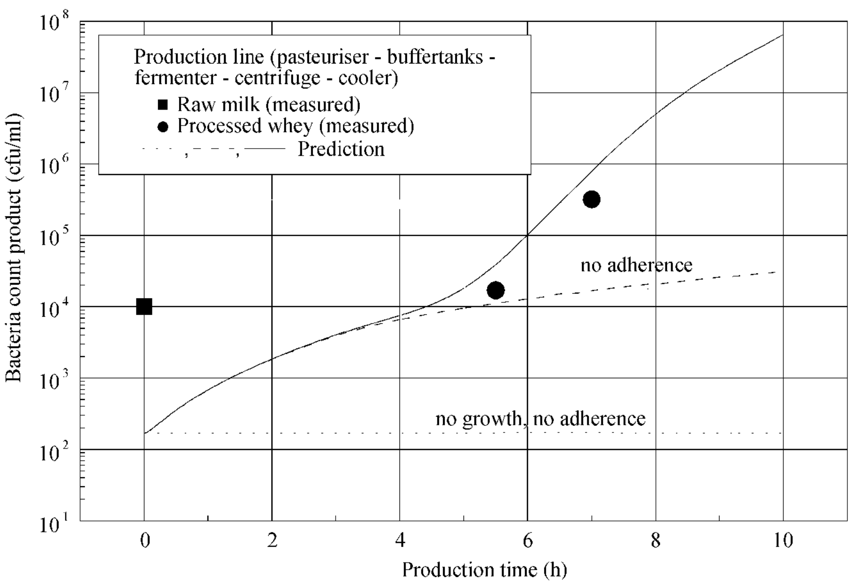

Fig. 16.9 Concentration of *Streptococcus thermophilus* in concentrate before spray drying related to the operating time: effect of local adherence and growth in the processing equipment.

Advanced models: Computational Fluid Dynamics
Computational Fluid Dynamics (CFD) has grown from a mathematical curiosity to become an essential tool in almost every branch of fluid dynamics. It allows for a deep analysis of the fluid mechanics and local effects in a lot of equipment. Most of the CFD results will give improved performance, better reliability, more confident scale-up, improved product consistency and higher plant productivity. However, it is only in recent years that CFD has been applied in the food processing area (Xia and Sun, 2002). CFD has been used to investigate the performance and design of dryers in the food industry. However, the design of spray dryers is heavily influenced by the complexity of air and spray flow patterns inside the dryers. Therefore, there is considerable scope for the application of CFD simulation, including optimum design of spray dryers and solutions for operational problems, such as wall deposition. Straatsma *et al.* (1999a, 1999b) developed a drying model utilising a turbulence model to calculate the gas flow field and showed that the drying model was an effective tool in giving indications how to adapt industrial dryers to obtain a better product quality or to optimise the drying performance of the unit.

During spray drying, agglomerates of powder particles are formed (see Fig. 16.10) which determine the instant properties of the powder (i.e. the ability to dissolve easily, quickly and completely). Agglomeration during spray drying is considered to be a difficult process to control. The main cause of this is the complex interaction of the process variables: the atomisation process, the mixing of spray and hot air and the collision of particles. As a consequence, agglomeration during spray drying is often regarded as a black box and is operated by trial-and-error.

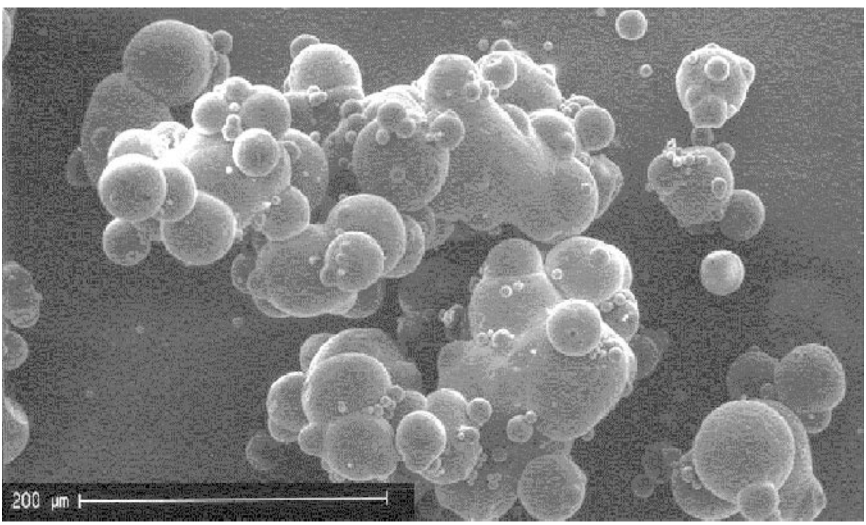

Fig. 16.10 SEM-photograph of spray dried and agglomerated powder.

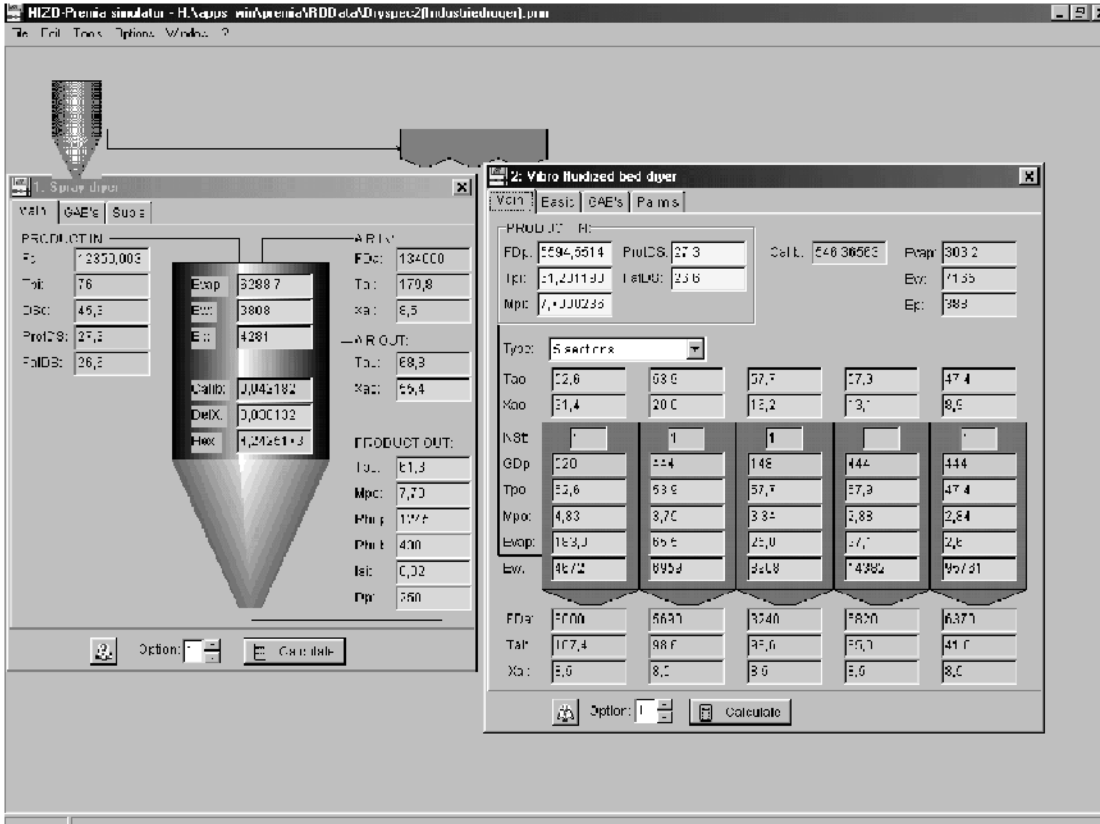

Fig. 16.11 The Premia flow sheeting system for parallel process and product evaluation (shown: DrySpec2).

It turns out that with CFD it is possible to predict agglomeration processes in spray drying machines (EDECAD, 2001). Based on the CFD model a second model is developed which establishes relations between the configuration of the drying installation (geometry, nozzle selection), process conditions, product composition and final powder properties. Important steps in the formation of agglomerated powders are atomisation, the mixing of spray and gas (collision of droplets, drying) and agglomeration of sticky particles. This second model can be used for control purposes.

Flow-sheeting and predictive models

The powder properties cannot be addressed to one mechanism or one unit-operation. This means that for the prediction of powder properties different models have to be coupled. For example, the production of milk powder is facilitated by a chain of unit-operations: standardisation, preheating, evaporation, etc. The composition of the raw materials and the applied preheating conditions affects the denaturation degree of the proteins. The denaturation degree affects the viscosity of the concentrate at the outlet of the evaporator and the solubility of the powder. The viscosity affects the droplet size distribution after atomisation in the spray dryer. The process operation also influences the operation costs.

For the dairy industry a (flow sheeting) system called Premia has been developed that enables the coupling of a variety of unit-operations generating a complete production chain (Smit *et al.*, 2001). In a library of product models (e.g. bacteria inactivation, enzyme inactivation, microbial spore inactivation, contamination, protein deposition, destruction of vitamins, formation of Maillard products, viscosity change, etc.) the connection is made between process operation and product properties. In Fig. 16.11 a screen shot of the Premia system is given, showing, for example, the spray dry module DrySpec2 (Straatsma *et al.*, 1991).

16.4 Process and product control

The main issue of the automatic control of spray dryers is a constant level of the moisture content of the powder. As illustrated in Fig. 16.12 a reduced standard deviation of the moisture content minimises the operating costs. Particularly in drying processing there is a trend to use more and more predictive models in the control strategy (see Fig. 16.13). In most cases these models are first-principle or neural network models (respectively the white and black box approaches). Only a few first-principle approaches have been described in the literature (Alderlieste *et al.*, 1984; Chen, 1994; Delemarre, 1994; Pérez-Correa and Farías, 1995). All these references are directed on moisture content only. Since more and more (predictive) models become available, it is possible to design control procedures focused on other powder properties such as insolubility and stickiness.

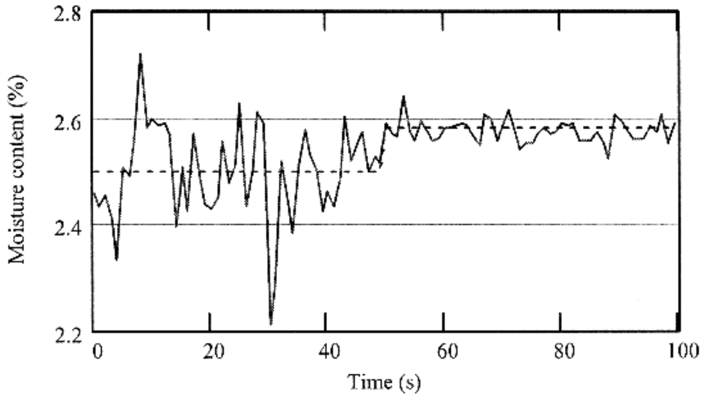

Fig 16.12 The effect of a well-defined automatic controller on the moisture content of powder, thereby reducing the operating costs.

Table 16.3 compares control approaches of predictive models and black box models. The predictive model approach is more flexible and robust to handle changes in the design and process operation. The advantage of the black box approach is that it needs less knowledge about the design and operation of the process equipment; an example for an evaporator is described by Verdurmen *et al.* (2002). Since the neural network approach is still considered as a special field of expertise, manufacturers of dryer installations have initiated cooperation with specialised software-houses.

16.4.1 On-line monitoring of moisture content of powder

The classical control strategy of spray dryers is based on the PID concept (Stapper, 1979). Modern dryers use the moisture content measured by infrared, resistive or capacitive measurements as a control variable. Manipulated variables are the thermal flux (air temperature, gas flow rate) or the concentrate flow rate. The choice of the product flow rate as the manipulated variable is

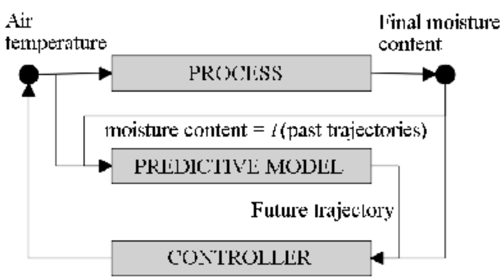

Fig 16.13 Example of a model-based control scheme.

Table 16.3 Comparison between two modelling approaches used for model-based control of dryers

Predictive model-based (first principle and reaction models)	Black box model-based (response and neural network models)
• Relatively high predictive power outside the operation point (location independent) • Process knowledge needed • Custom-made dryer models • Few measuring points needed	• Less predictive power outside the operation point (location dependent) • No process knowledge needed • Standard software tools available (process independent) • Many measuring points needed for model training • Training after every change in process configuration

generally cheaper but it should be avoided in case of continuous flow production because it modifies locally the production capacity and creates larger buffers. Continuous on-line monitoring allows a full realisation of process capability and operation of the spray dryer closer to the upper specification limits of the dryer. Over-drying, which can cause damage to the product, is avoided and both production yield and productivity are maximised. In addition, the optimum product shelf-life is achieved and avoidance of over-drying provides a saving on energy costs. Amongst others, NIR techniques provide continuous, high-speed measurements of the moisture content of milk and other powders (see also Chapter 21). In addition, measurement of protein and fat content in milk powder is also feasible. An example of an on-line NIR gauge mounted below an industrial fluid-bed dryer (part of a spray dryer for milk powder) is given in Fig. 16.14. The possibility of measuring the moisture content of powder on-line also enables a feedback signal to be given to the control system of the dryer.

16.4.2 Predictive model-based control

Predictive models as described turn out to be an effective tool to translate scientific knowledge to practical applications in the food factories. The most effective way to ensure the benefits of using predictive models would be to integrate them into process control systems. Based on actual process data and the composition of the raw materials, the models can predict the state of the process (e.g. amount of fouling, biofilm thickness, energy usage) and the state of product (degree of contamination, stability, texture). This means that the process can be controlled on product specifications instead of process conditions. By adding cost-related models the system can continuously optimise the production process with respect to the product quality and the production costs (De Jong *et al.*, 2002c).

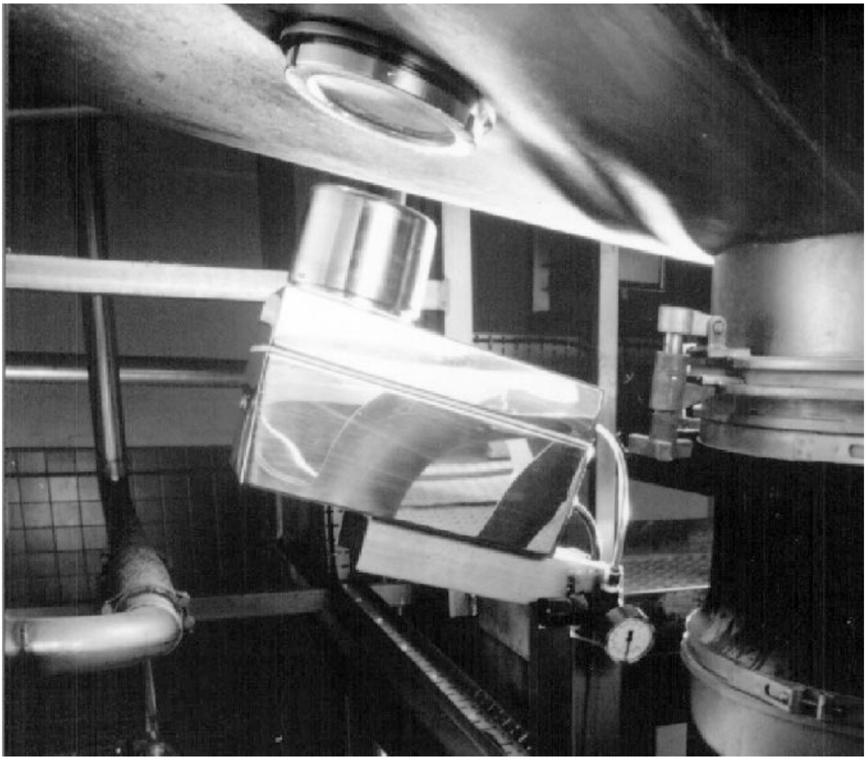

Fig. 16.14 On-line NIR gauge mounted below a fluid bed (Courtesy of NDC Infrared Engineering).

In Fig. 16.15 this approach is shown in general terms. Based on process design (e.g. dimensions, apparatus configuration, in-line measured process conditions) the temperature–time history of the product is calculated with the process model. Together with the given composition this information is used to predict the product properties using the kinetic product models. In addition the operating costs per tonne of product are estimated based on the fouling and contamination models. The predicted product properties are compared with the given desired product properties. In the optimisation module the production process set-points are optimised to meet the desired product properties as closely as possible with minimum operating costs.

In the ideal situation the process is controlled based on the desired product specifications and minimum operating costs. The system corrects itself automatically when:

- Fouling changes the temperature–time history of the concentrate at the inlet of the spray dryer
- The product specifications change
- The composition of the raw materials changes
- Disturbances occur (e.g. temperature changes, flow instabilities).

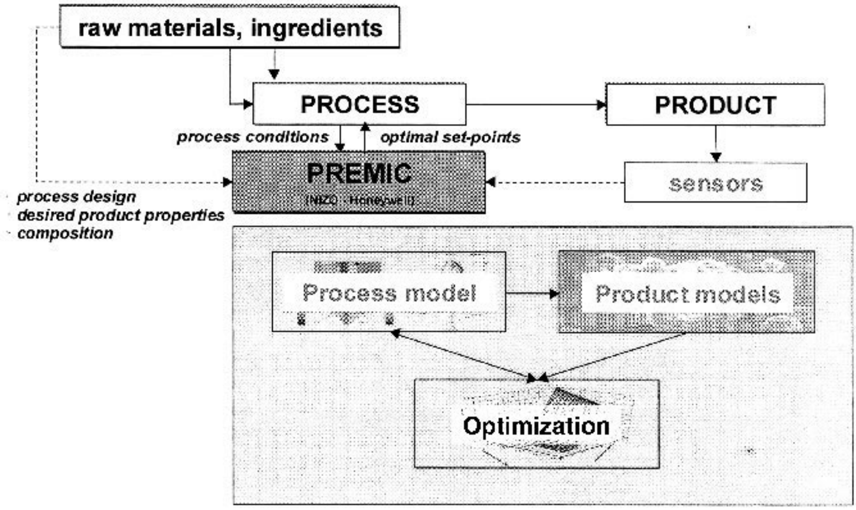

Fig. 16.15 Schematic representation of the PREMIC control system (PREdictive Models for Industrial Control).

Optimisation algorithm

An essential part of the control procedure based on predictive models is the optimisation module. The main control factors for product and process optimisation are the temperature–time relationship and the configuration of the processing equipment. In order to determine the optimal values of the control variables, a general objective function is used:

$$F(u, x) = \alpha c_{\text{quality}}(u, x) + \beta c_{\text{operation}}(u) \qquad 16.7$$

where *u* is a vector of process control variables (e.g. temperature, flow) and *x* is a vector of desired product properties related to food quality and safety. The value of c_{quality} depends on the outcomes of the predictive models for contamination and transformation of food components, and $c_{\text{operation}}$ is related to the operating costs. The optimal configuration and operation of a production chain is achieved by minimisation of the objective function. To avoid trivial and undesired solutions, the weight factors α and β are introduced. These weight factors give the relative importance of each term of the objective function. For example, too high a value of β may result in a very clean and cheap production process but an inferior product quality.

Example of process and product optimisation

To illustrate the application of the procedure described for optimising food production chains, the following case study has been performed. A heating process with a capacity of 40 tonnes skim milk per hour consists of a regenerative section, a heating section and two holding sections and a cooler. In Fig. 16.16 the scheme of the process is shown with some preliminary

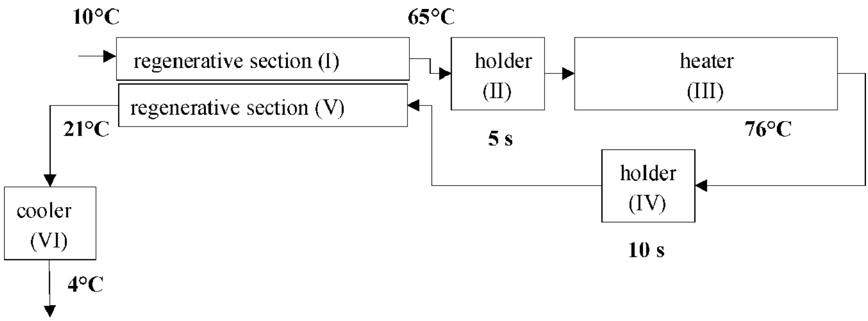

Fig. 16.16 Example process (upstream dryer).

temperatures and residence times. In order to have a process model the equipment is transformed to a cascade of model reactors. The objective function is defined as:

$$F(u,x) = \sum_{i=1}^{3} \alpha_i \left(\frac{x_{ides} x_i(\mathbf{u})}{x_{ides}} \right)^2 + F_{\cos t} \qquad 16.8$$

where

$$F_{\cos t} = \frac{c_{\text{operation}} \cdot t_{\text{operation}} + c_{\text{solids}} \cdot t_{\text{production}} \cdot \iint_{x,t} J_{x,t} \text{d}t \ \text{d}x}{t_{\text{production}} \cdot \phi} \qquad 16.9$$

where α_i is a weight factor for the relative importance of product property x_i, $x_{i,\text{des}}$ is the desired product property, **u** is the set of control variables, c are costs, t is time, the integral term is the total amount of deposits after 1 h of production, ϕ is the capacity of the process in tonnes per hour,

$$t_{\text{production}} = \frac{t_{\text{operation}} \cdot t_{\text{run}}}{t_{\text{run}} + t_{\text{cleaning}}} \qquad 16.10$$

and the production time per run:

$$t_{\text{run}} = t \quad \text{if } C_{\text{s.thermophilus}} > 0.0001 \text{ cfu ml}^{-1} \qquad 16.11$$

The weight factor α_i is introduced to avoid trivial and undesired solutions. The chosen values of the weight factors are determined by the relative importance of the different product properties. However, since the relationship between the weight factor values and the optimisation results are not clear in advance, the determination of the weight factor value is an iterative process in consultation with industrial experts.

In this case the control variables (**u**) are limited to two: the heating temperature and the residence time at this temperature in the second holder section. With two control variables surface plots can present the results of the computer model simulations. Figure 16.17 shows the results of the objective function evaluations. The optimal set-points are a heating temperature of 78.7°C

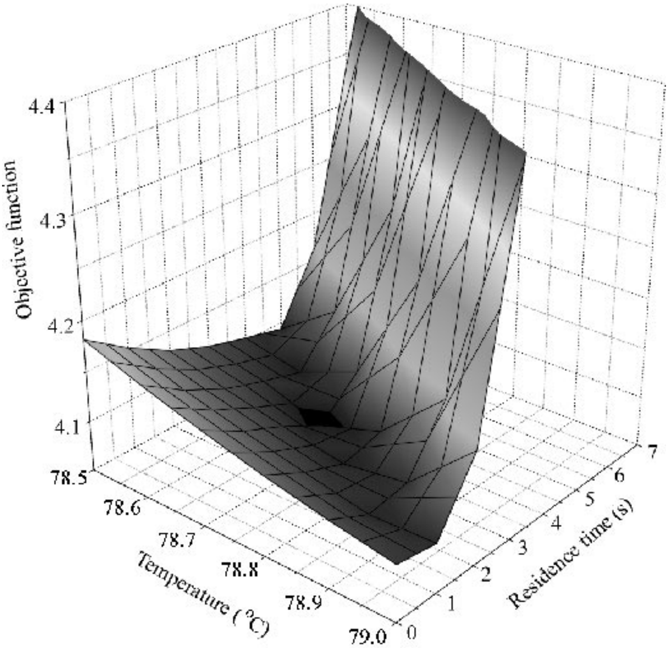

Fig. 16.17 Evaluation of the objective function.

and a residence time of 3 s. As compared to the initial preliminary design (10 s, 76ºC) the operating costs could be decreased by 14%. At an annual production of 4700 h this means an estimated cost saving of Euro 58 000. More details are given by De Jong *et al*. (2002c). Detailed studies show that cost reductions of more than 50% are feasible (De Jong, 1996).

16.5 Ensuring process safety

One of the hazards in producing powders is fire in a drying installation. Fire and the resulting explosion risks can be reduced by taking technical and organisational measures (IDF, 1986). Fire and explosion protection can be obtained using relief venting, automatic suppression or inerting. Venting is the most frequently used method, see also Fig. 16.18. Protection by automatic suppression (see Fig. 16.19) is usually straightforward, although dryers of very large volume may present problems due to the airflow through the drying chamber removing the suppressant agent (Palmer, 1990). However, considerable damage may still result, because the available explosion or fire protection systems are only activated when the explosion or fire has actually started. About 80% of the recorded fires were preceded by smouldering of powder. Deposits of milk powder in spray dryers may undergo exothermic reactions between the milk constituents and this may lead to self-ignition and smouldering. Smouldering

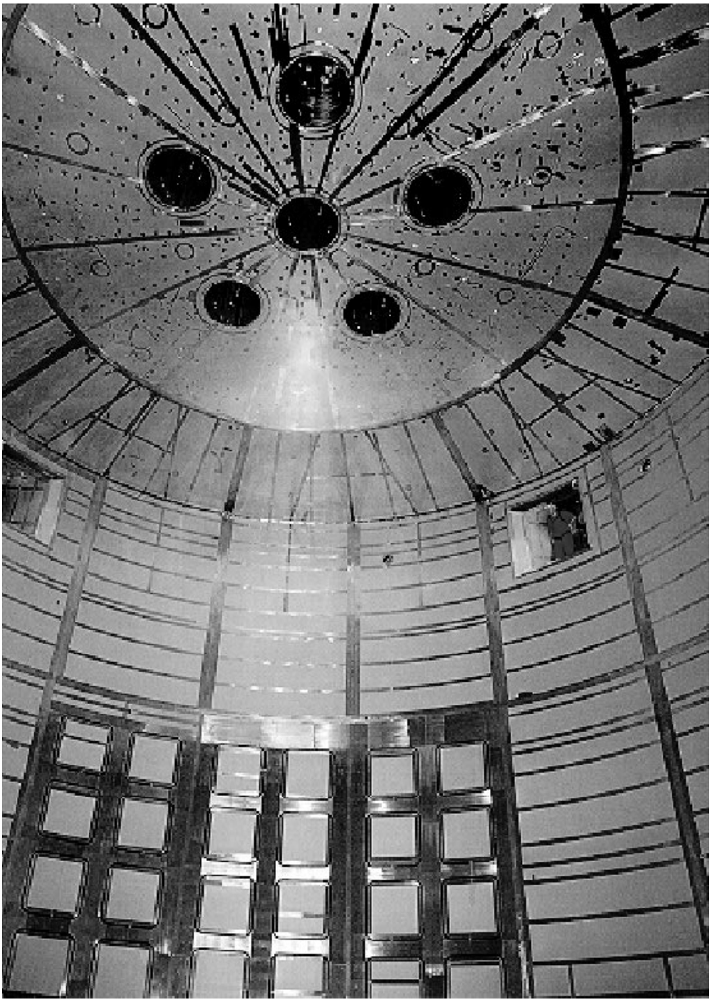

Fig. 16.18 Inside of an industrial spray dryer with atomisation units at the top and explosion venting panels at the spray chamber wall (courtesy of Carlisle Processing Systems – Friesland).

deposits may, if the occasion arises, fall down and initiate an explosion in the lower part of the drying chamber (cone) where the dust concentration often considerably exceeds the lower explosion limit (Skov, 1986). Once the milk powder is smouldering it produces a significant amount of carbon monoxide (CO). It has been shown that this increase of CO can be detected by a sensitive CO analyser which makes it possible to detect a smouldering lump of powder before the powder actually takes fire (Steenbergen *et al.*, 1991). Figure 16.20 shows a part of the measuring system. The system comprises an air sample line from the inlet of the dryer, an air-treating unit for cleaning and drying the air issuing from the outlet of the dryer, a CO analyser and, if necessary, a control

Fig. 16.19 Commercial explosion suppression system mounted on top of a cyclone (courtesy of Anhydro A/S).

system for consecutive performance of the measuring cycle. Nowadays an increasing number of CO detection systems are operating on an industrial scale as early-warning systems for fire, and the CO detection system is linked to the control system of the dryer systems to perform automatic shutdown.

Requirements for the safety and health protection of workers potentially at risk from explosive atmospheres will become more strict from 1st July 2003 when the European Council Directive 1999/92/EC (also known as ATEX 137) will become operational. This directive, which makes area classification, documentation, inspection, verification, training and warning signs legal requirements, applies to all new hazardous area equipment from this date. Existing workplaces have a further three years before the full requirements of the directive are applied.

The employer is required to take all reasonable measures to prevent the formation of an explosive atmosphere in the workplace. Where this is not

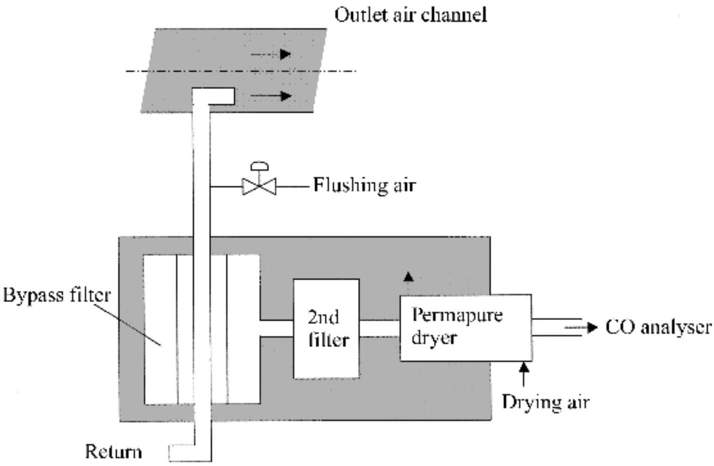

Fig.16.20 Set-up of a CO measuring system for dryers.

possible, measures must be taken to avoid the ignition of any potentially explosive atmosphere (prevention). Furthermore, the effects of any explosion must be minimised in such a way that workers are not put at risk (protection). The employer will be required to carry out an assessment of the likelihood that an explosive atmosphere will occur, likelihood of ignition and scale of effects. In carrying out this assessment the employer will be required to produce an Explosion Protection Document.

An EU-project group, 'Risk Assessment of Unit Operations and Equipment', reported on a risk assessment for spray dryers producing milk powder (RASE, 2000). They concluded that an explosive atmosphere in the form of a cloud of combustible milk powder in air is present continuously and cannot be eliminated. Consequently the prevention of ignition sources should have the highest priority and self-ignition of milk powder deposits is considered to be a major risk; other ignition sources are considered to be a minor risk. Reducing the risks caused by self-ignition focuses at eliminating fire events as much as possible by taking preventive fire and explosion measures, such as temperature monitoring, CO detection or fire suppression systems. These preventive measures should become part of the inherently safe design of the spray chamber, but should also be considered for the fluid beds and filters. In addition, protective systems should also be applied, for example pressure-relief systems or explosion suppression systems (RASE, 2000).

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