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Original article

Modelling spray drying processes for dairy products

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Abstract – NIZO food research (The Netherlands) has been working for the food industry, the dairy industry in particular, for over 50 years. During the past 15 years NIZO food research has put a lot of effort into developing predictive computer models for the food industry. Nowadays the main challenges in the production of powders are the development of specialities (having a high added value) and the reduction of processing costs. For this, the production capacity of available installations is maximised and the process conditions are directed towards minimal fouling of equipment, minimal product losses and reduction of energy consumption. On-line product quality control is implemented as far as possible. For these purposes predictive computer models have proven to be very helpful. These models also reduce the number of costly and time-consuming production trials needed for the development of new products or processes. In this article an overview is given of various industrial applications of predictive computer models for spray drying of dairy products. New applications in the field of computational fluid dynamics (CFD) and developments in model predictive control are also discussed. It is expected that these new applications will make it possible to adjust drying equipment more quickly to new products and will reduce variations in product properties to a large extent.

Milk / spray dryer / evaporator / modelling / control / powder property

Résumé – **Modélisation de procédés de séchage par atomisation pour les produits laitiers**. Le NIZO food research travaille depuis de nombreuses années sur la mise au point de modèles prédictifs informatisés pour l'industrie alimentaire. Actuellement, les principaux défis dans la production de poudres sont le développement de spécialités (à forte valeur ajoutée) et la réduction des coûts de production. Dans ce but, la capacité de production des installations disponibles est portée au maximum, et les conditions opératoires sont établies pour avoir le colmatage minimal de l'équipement, les pertes minimales de produit et pour réduire les consommations d'énergie. Le contrôle qualité du produit en ligne est mis en œuvre aussi loin que possible. Pour ces raisons, des modèles prédictifs informatisés se sont révélés très utiles. Ces modèles réduisent également le nombre d'essais couteux et longs nécessaires pour le développement de nouveaux produits ou procédés. Dans cet article, une revue est

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présentée sur les applications industrielles variées des modèles prédictifs informatisés pour sécher par atomisation les produits laitiers. Les nouvelles applications dans ce domaine de l'estimation de la dynamique des fluides et les développements dans le contrôle par modèle prédictif sont aussi discutés. Ces nouvelles applications devraient permettre d'ajuster les équipements de séchage plus rapidement aux nouveaux produits et réduire en grande partie les variations des propriétés du produit.

Lait / séchage par atomisation / évaporateur / modélisation / contrôle / propriété de la poudre

1. INTRODUCTION

NIZO food research (The Netherlands) has been working for the food industry, the dairy industry in particular, for over 50 years. During the past 15 years NIZO food research has put a lot of effort into developing predictive computer models for the food industry. The quality of food powders is based on a variety of properties, depending on the specific application. In general the final moisture content, the bulk density, the insolubility index and the instant properties are of primary importance. Nowadays the main challenges in the production of powders are the development of specialities (having a high added value) and the reduction of processing costs. For this, the production capacity of available installations is maximised and the process conditions are directed towards minimal fouling of equipment, minimal product losses and reduction of energy consumption. On-line product quality control is implemented as far as possible. For these purposes predictive computer models are very helpful [7].

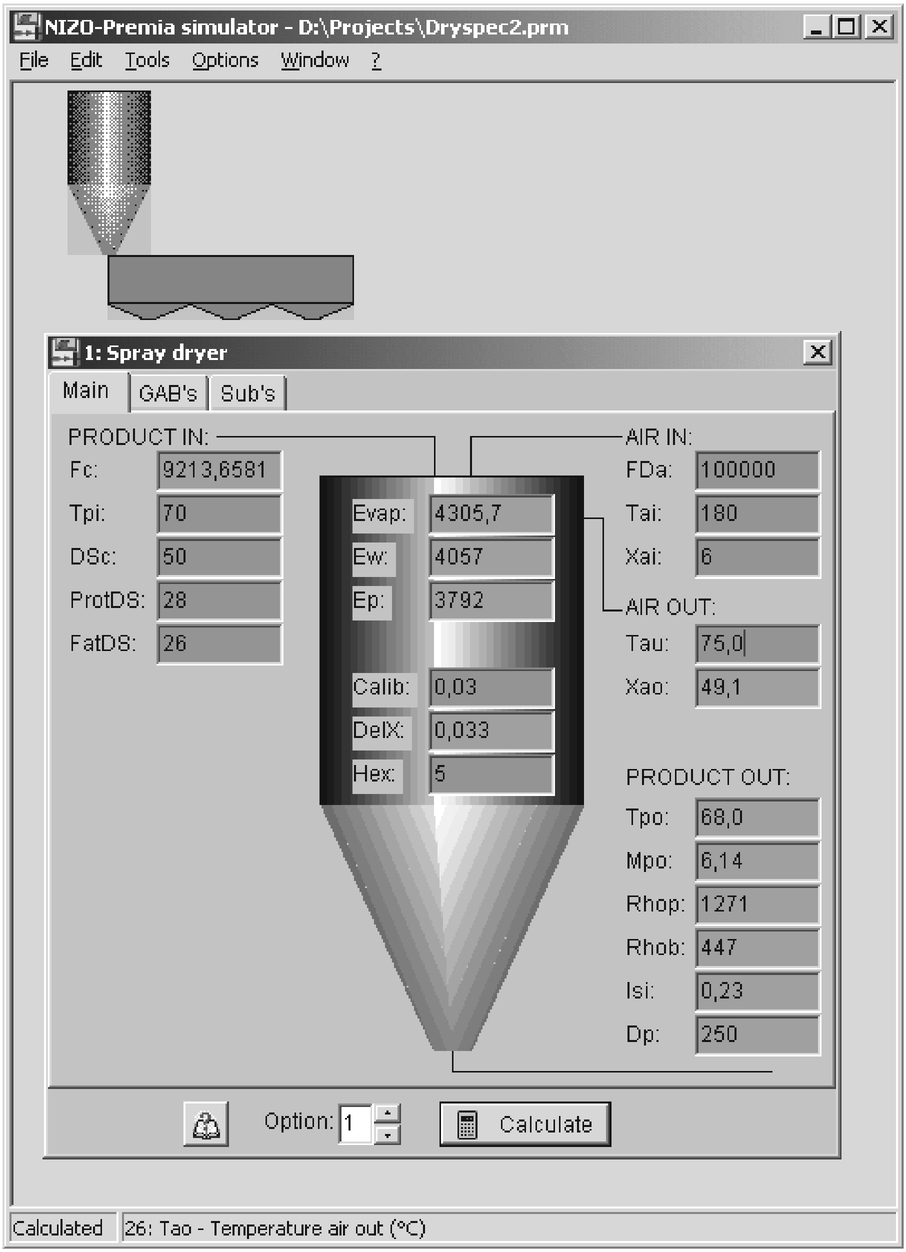
This article will give an overview of the various applications of predictive computer models for spray drying of dairy products. New applications in the field of computational fluid dynamics (CFD) and developments in model predictive control will also be discussed.

2. PREDICTIVE MODELS FOR SPRAY DRYING

Two different predictive models for spray drying of dairy products have been developed, implemented and industrially validated by NIZO food research. These two models, DrySPEC2 and DrySim, will be described below. The development of predictive models is an ongoing process; at this moment a consortium of universities and companies (with NIZO food research as the co-ordinator) is developing a model to predict the agglomeration in spray drying installations. This project is also briefly described below (Sect. 2.3).

2.1. Relation between the process conditions of the spray drying process, energy consumption and powder properties: DrySPEC2

The first drying model that was developed by NIZO food research is DrySPEC2 (DRYer System for Property and Energy Control). This computer model describes the relation between the processing conditions of the drying process, energy consumption and the properties of the powder produced for a two-stage dryer [6]. The purpose of this model is to establish the process conditions that ensure optimal exploitation of the capabilities of existing drying installations with regard to energy consumption and the powder properties. This model assumes a near-equilibrium state of water vapour pressure between powder and outlet air, which eliminates the need for a detailed description of heat and mass transfer phenomena during the drying process. In Figure 1 a screenshot of DrySPEC2 is shown. The model is integrated in a user-friendly interface in which other software modules can also be accessed.



PRODUCT IN:
Fc: 9213,6581
Tpi: 70
DSc: 50
ProtDS: 28
FatDS: 26

Evap: 4305,7
Ew: 4057
Ep: 3792
Calib: 0,03
DelX: 0,033
Hex: 5

AIR IN:
FDa: 100000
Tai: 180
Xai: 6

AIR OUT:
Tau: 75,0
Xao: 49,1

PRODUCT OUT:
Tpo: 68,0
Mpo: 6,14
Rhop: 1271
Rhob: 447
Isi: 0,23
Dp: 250

Option: 1

Calculated
26: Tao - Temperature air out (°C)

Figure 1. Screenshot of NIZO DrySPEC 2 with user-friendly interface.

The model uses mass and thermal balances, psychrometric relations and sorption isotherms and acts partly as a black box model. A calibration must be carried out once, in order to tune the model to the specific dryer, taking into account the heat losses of the installation and the deviation from equilibrium state between powder and outlet air. The standard setup of this model is for a two-stage dryer (spray chamber and fluid bed dryer), but it has also been adapted to other types of dryers, e.g. containing an internal fluid bed.

DrySPEC2 has successfully been implemented for the production of dairy products such as skim milk, whole milk and whey permeate. The results obtained in increasing the earning capacity of industrial spray dryers are: up to 20% increase in capacity, limiting the deviation in moisture content to lower than 0.05% (for example, by adjusting the process to variations in the total solids content of the feed or moisture content of inlet air) and an annual energy reduction potential of about 250 000 m^3 natural gas per installation.

2.2. Simulation of flow patterns, local drying behaviour, fouling of spray dryers and insolubility index: DrySim

In order to simulate the drying process in more detail, it is necessary to gain insight into the flow pattern, local temperature and local moisture content of the air and the temperature-time history of drying particles [5]. The flow pattern of air depends on the geometry of the dryer and the location and design of the air inlet and air outlet channels. The trajectories followed by the (drying) particles depend not only on the air-flow pattern but also on the position and method of atomisation. At NIZO food research the drying model DrySim was developed as a tailor-made simulation program for spray dryers, making use of computational fluid dynamics (CFD) techniques. DrySim is a two-dimensional simulation model of a spray dryer. It calculates the flow pattern, temperature and moisture content of air, the trajectories of the atomised particles and the drying behaviour of individual particles. The gas-flow is described by the time-averaged Navier Stokes equations in combination with the standard k-ε turbulence model. Source terms account for the effect of the droplet on the flow. A particle tracker, based on the equation of motion, is used to simulate the particle trajectories. Since the particles affect the gas-flow (and vice versa), an iteration procedure is used to solve the equations (see Fig. 2). The drying of droplets is influenced by both external transport phenomena (from particle surface to surrounding air) and internal transport phenomena (diffusion of water within particles). The differential equation that describes the

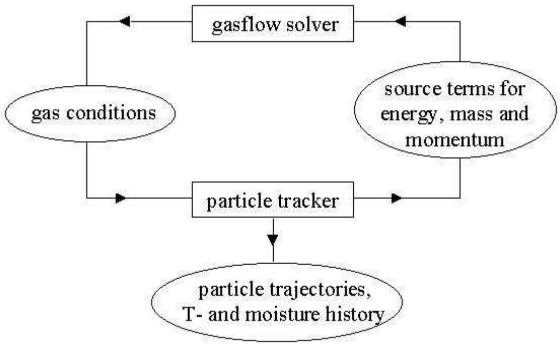


Figure 2. NIZO DrySim calculation flowchart [7].

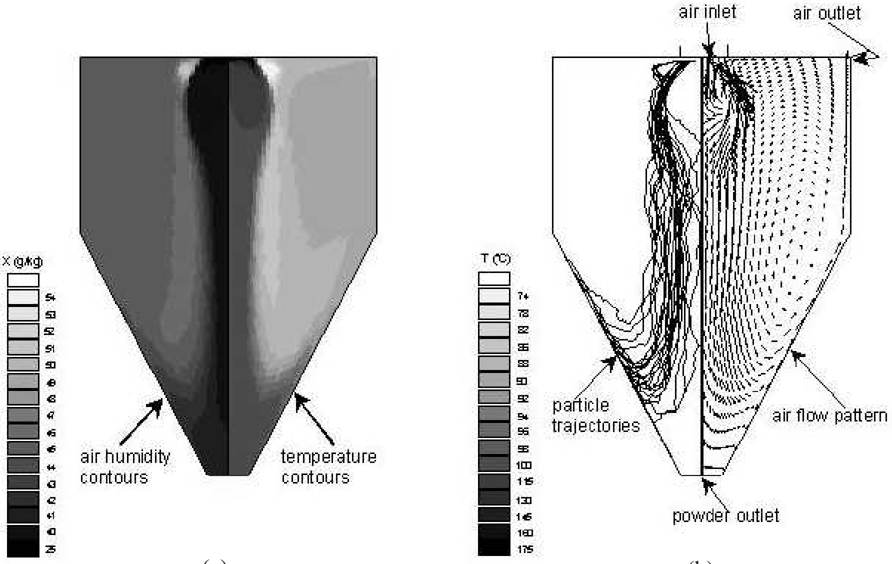
diffusion process of spherical particles is solved numerically, simultaneously with the equations for external heat and mass transfer [7]. In order to obtain reliable results, it takes several hours using a personal computer (800 MHz, 128 Mb RAM) to carry out one simulation.

Sub-models for the formation of insoluble material or for describing the stickiness of particles have been added to DrySim [8].

Three industrial cases will be described below, which show that DrySim is an effective tool for giving indications of how to adapt industrial dryers, for example to obtain a better product quality, a higher capacity or to reduce fouling.

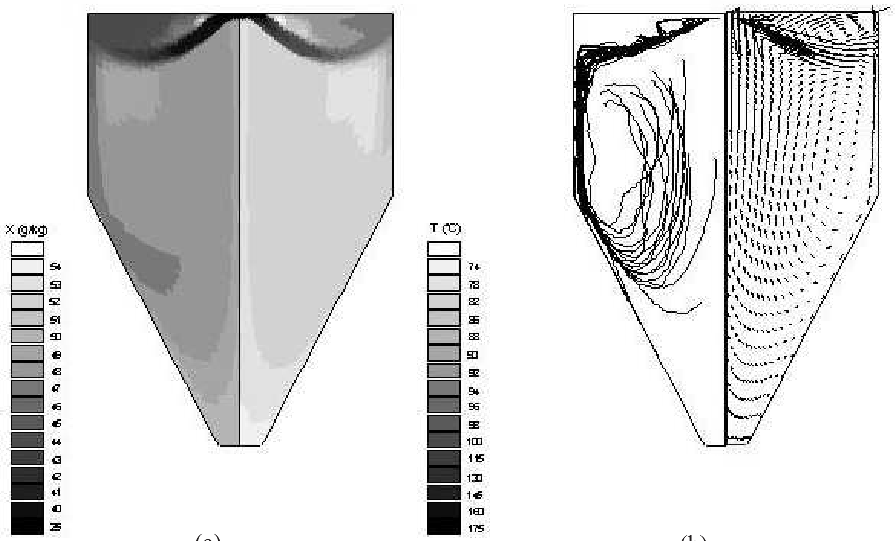
2.2.1. Case study 1

DrySim model simulations are widely used at the request of the dairy industry and suppliers of drying equipment to simulate existing spray dryers or new designs. About 50 spray dryer configurations have been simulated up to now. An example is the simulation of an existing spray dryer with rotary-wheel atomisation [7]. This dryer sometimes exhibited strange behaviour, and a short cut air-flow from the inlet to the outlet was suspected by the operators. According to the supplier, a short cut flow was out of the question. To get a better understanding of the behaviour, simulations were carried out. Figure 3 shows the temperature and air humidity in the dryer as contours (Fig. 3a) and the simulated flow pattern of the air and particle trajectories (Fig. 3b). When the rotary speed of the atomiser is low, droplets leave the atomiser with an average velocity of 58 m·s^{-1}. The air inlet is placed at the centre of the ceiling and the inlet air-flow is directed straight downwards. In the dryer there is a main circulation air-flow, which is downwards at the centre axis and upwards at the outer side. A part of the air-flow leaves the dryer at the outlet, which



(a) (b)

Figure 3. Computational simulation (NIZO Dry-Sim) of an industrial spray dryer. Initial droplet velocity: 58 m·s^{-1}: (a) air humidity and temperature contours; (b) simulated air-flow patterns and particle trajectories.



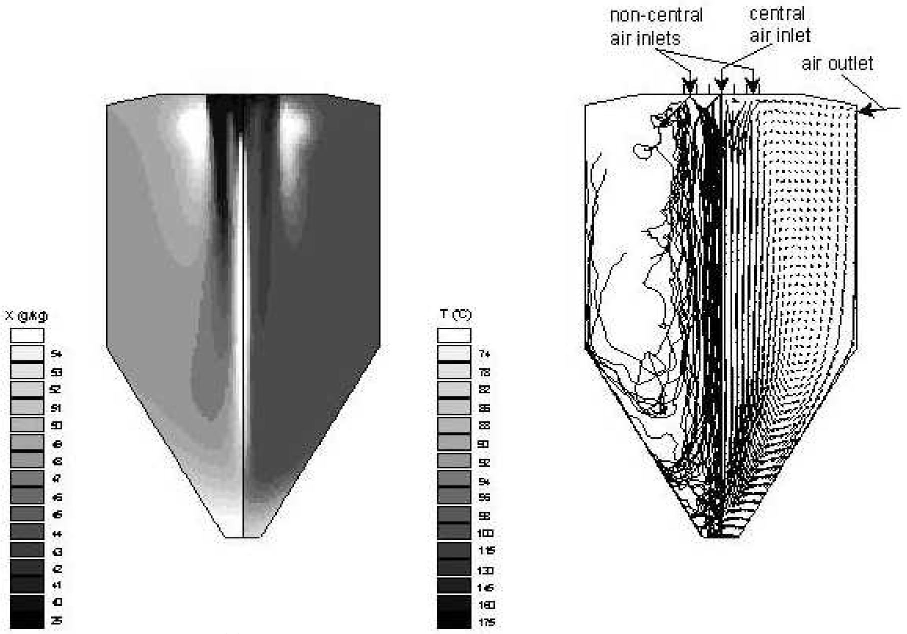
(a) (b)

Figure 4. Computational simulation (NIZO Dry-Sim) of an industrial spray dryer. Initial droplet velocity: 150 m·s^{-1}: (a) air humidity and temperature contours; (b) simulated air-flow patterns and particle trajectories.

is positioned at the upper side of the cylindrical chamber; a smaller part of the airflow recirculates towards the air inlet. The air that reaches the outlet is cooled to about 90 °C due to evaporation of water. Over the years, the capacity of the dryer and the rotary-speed of the atomiser have been gradually increased. In this dryer, the momentum exchange from the atomised spray-droplets to the air has a strong influence on the flow pattern, as is shown in Figure 4. The figure shows the results of a simulation with a higher rotary speed (droplet velocity 150 m·s^{-1}). The main air-flow has reversed compared to Figure 3 and there is a circulation of hot air in the upper part of the dryer. The temperature of the outlet air is now much higher (Fig. 4a). This simulation shows that the operators' idea was correct: at a high rotary speed, reversal of the main air-flow and a short cut of hot air from inlet to outlet may be expected. The dryer concerned has now been reconstructed for high-pressure nozzle atomisation.

2.2.2. Case study 2

Another example is the simulation of an industrial spray dryer for the production of a powder with high lactose content. The dryer was equipped with one central and several non-central air inlet channels and with nozzle atomisers [7]. This dryer had serious fouling problems in the bottom part (cone). The simulation as shown in Figure 5 indicated clearly that the powder particles collided with the cone wall when the airflow reversed in the conical part of the dryer. Under these conditions the particles were not dry enough and were very sticky. Furthermore, the simulations indicated that the thermal load of the particles atomised in the central air inlet was much higher than that of the particles atomised in the non-central air inlets due to the temperature distribution in the dryer. According to new simulations, adapting the cone angle would reduce the fouling problem. However, this would be an expensive modification since



(a) (b)

Figure 5. Computational simulation (NIZO Dry-Sim) of an industrial spray dryer: (a) air humidity and temperature contours; (b) simulated air-flow patterns and particle trajectories.

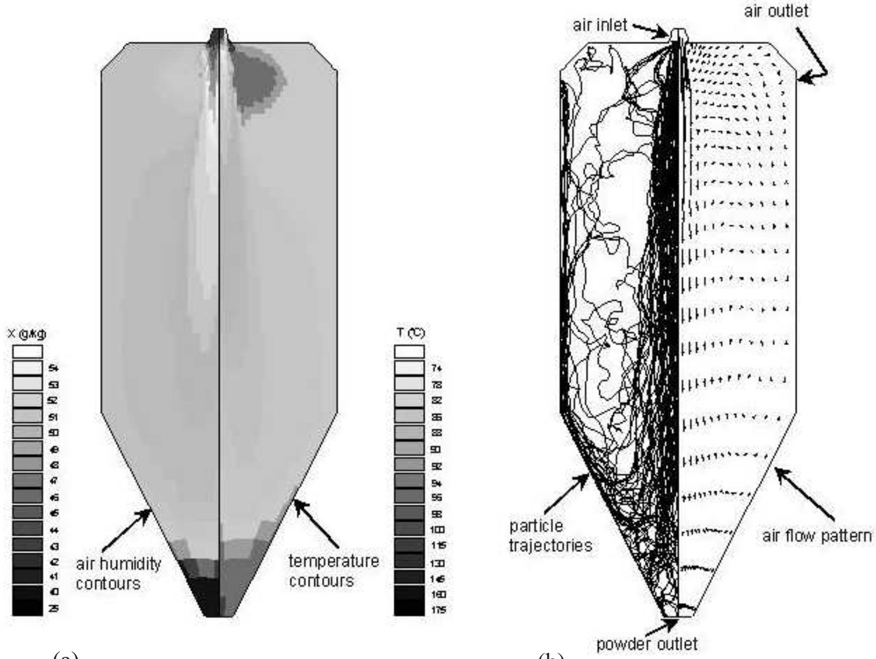
the height of the building was limited. Reconstruction of the air inlet has now solved the problem, mainly by changing the diameters of the air inlet channels.

2.2.3. Case study 3

A third example is the simulation of an existing industrial two-stage spray dryer (see Fig. 6), for which it was planned to increase the capacity by 20% by increasing the air-flow and by modifying the existing fluid bed. The simulations using DrySim showed that the air temperature also needed to be increased in order to achieve the required capacity increase. This would also result in an energy reduction of 2% per mass volume powder. The disadvantage of these changes would be a slight increase in the insolubility index of the powder. New simulations showed that replacing central atomisation (nozzles positioned under the centre of the air inlet channel) by lateral atomisation (nozzles positioned at the periphery of the air inlet and directed to the centre) would under similar process conditions lead to a lower thermal load of the product. After modifying the nozzle geometry, the predicted effect proved to be correct.

2.3. Simulation of agglomeration in spray drying installations: the EDECAD project

During spray drying, agglomerates of powder particles are formed (Fig. 7) which determine the instant properties of the powder (i.e. the ability to dissolve easily, quickly and completely). Agglomeration



(a) (b)

Figure 6. Computational simulation (NIZO Dry-Sim) of an industrial spray dryer. (a) air humidity and temperature contours; (b) simulated air-flow patterns and particle trajectories.

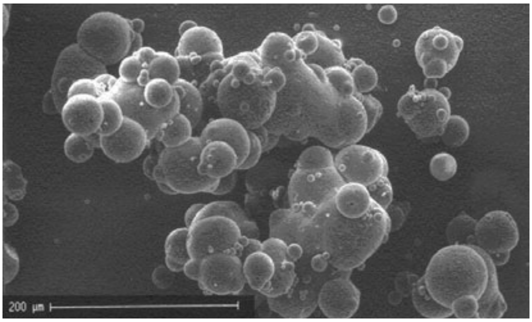


Figure 7. SEM-photograph of spray dried and agglomerated powder.

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.

At the beginning of 2001 a large international research and technological development project started with the aim of developing an industrially validated (computer) model, using CFD technology, to predict agglomeration processes in spray drying machines. This project, initiated and co-ordinated by NIZO food research, is titled EDECAD (Efficient DEsign and Control of Agglomeration in spray Drying machines) and is sponsored by the EC Fifth Framework Programme within the research programme "Competitive and Sustainable Growth". The main result of the EDECAD project will be a so-called "Design Tool", which will establish relations between the configuration of the drying installation (geometry, nozzle selection), process conditions, product composition and final powder properties [4]. The Design Tool will be validated on a pilot-plant scale and an industrial scale. This Design Tool is envisaged to be a powerful tool for designing and optimising spray drying and agglomeration machinery. The project is expected to be finished at the beginning of 2004.

3. ON-LINE QUALITY CONTROL

In general, two types of control strategies can be distinguished. The first strategy is focused on maintaining constant values of process conditions, such as temperatures, flows and pressures. The idea is that constant process conditions will result in constant product quality. A more recent second control strategy is based on indirect or direct control of the desired product quality parameters. In this case, the set-points of the process conditions are determined by mathematical models which describe the interactions between process and product properties [2]. At present, the models used are black box models with little or no physico-chemical background. In Section 3.1. an example is presented using these black box models for feed-forward control of evaporators and spray dryers.

In the very near future, it is expected that physico-chemical predictive models will also be applied to model-based control. An example of a research project in this area is given in Section 3.2.

3.1. Feed-forward control of evaporators and spray dryers

To obtain a high-quality powder, a constant dry matter content in the concentrate produced in the evaporator preceding the drying process is necessary. The occurrence of changes in the dry matter content in the feed to the dryer is one of the major sources of disturbance in the drying process [2]. 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 is theoretically possible. This is in order to reduce the risk of too high a viscosity of the concentrate. Less variation in the dry matter content of the concentrate enables a higher set-point and thus also improves the energy efficiency of the powder production process. When using conventional control technology, such as single-loop proportional-integral-derivative (PID) controllers, the long time delay from input (e.g. flow or dry matter content of milk fed to the evaporator) to output (e.g. total solids content of concentrate by controlling the steam supply) will result in a relatively long period of off-spec concentrate. Modern design methods for multivariable control make it possible to design compensators that reduce or eliminate the off-spec period. For the design of such a multivariable control system one should determine the dynamic behaviour of the evaporator involved. This can be done either by using a physical model simulating the dynamic behaviour, or by carrying out step-response measurements on the actual evaporator and using system identification techniques to draw up a black box model [9]. The first approach is more flexible and robust for handling changes in the design and process operation. The advantage of the latter approach is that it requires less detailed knowledge about the design of the evaporator [9]. Also, in drying processes there is a trend of using more and more predictive models in the control strategy. The main issue for the automatic control of spray dryers is to achieve a reduced variation in the moisture content of the powder, enabling a higher set-point for the moisture content, which greatly reduces the operating costs [1, 2].

3.1.1. Case study

An industrial case is the design and implementation of a feed-forward control system for a four-stage falling-film evaporator with thermal vapour recompression. This control system contains a feed-forward compensation for the dry matter content of the feed to the evaporator (e.g. by measuring the density of milk using an in-line sensor), a feed-forward compensation for flow to the evaporator and a feed-back control system using the measured density (in-line sensor) of the concentrate. The dry matter content of the concentrate is controlled by adjusting the steam supply to the evaporator. In Figure 8 a schematic presentation of this feed-forward control system is given, illustrating how a variation in input (dry matter content of the feed, feed flow), output (dry matter content of the concentrate) or set-point of the dry matter content of the concentrate will affect the steam supply to the evaporator. Based on step-response measurement, the specific control algorithm is designed and implemented in the existing programmable logic controller (PLC) of the evaporator.

This new feed-forward control system has decreased the standard deviation in the dry matter content of the concentrate from 0.31% to 0.19% ($m \cdot m^{-1}$). Compared to a simple control system, it is now possible to increase the set-point of the dry matter content of the concentrate by at least 0.7% ($m \cdot m^{-1}$), resulting in an annual energy saving of 10 000 Euros based on a nominal capacity of 30 m^3 milk per hour. The capacity of the evaporator can now easily be adjusted to the capacity of the spray dryer without large variations in dry matter content. It is estimated that as a result of this, the set-point for the moisture content of powder can also be increased by about 0.07%, which will result in an annual energy saving of 50 000 Euros.

3.2. Model predictive control using physico-chemical models

For 15 years now, NIZO food research has been involved in the development of models that predict product parameters such as viscosity, maximum level of contamination, taste, etc. [2, 3]. Many of these have been applied with great success in industry, sometimes resulting in the reduction of production costs by up to 50% and improvement of product quality. As the most

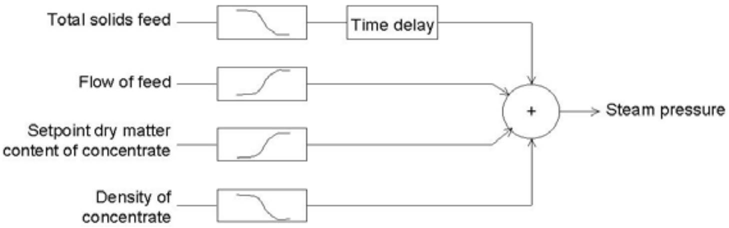


Figure 8. Scheme of a feed-forward control system for a multiple-effect falling-film evaporator.

recent project, NIZO food research has now started a joint development together with Honeywell, the world leader in process control systems, of a process control system for the food industry. Models that predict product properties in relation to the process and the product composition will be integrated in software for automatic process control for the food industry. It is expected that a first prototype will be in use by the end of 2002.

4. CONCLUSIONS

Predictive computer models have proven to be effective in reducing processing costs and improving product quality in the food industry. These models also reduce the number of costly and time-consuming production trials needed for the development of new products or processes. Models are also successfully used for on-line control systems, needed to maintain a constant product quality. The development of models for the food industry is an ongoing process. The integration of physico-chemical models, computational fluid dynamics and control systems will enable an optimal use of available knowledge, experimental data and computing speed. As a result, it will soon be possible to predict more accurately the optimal process settings for the desired powder properties and to control the quality on-line. This will make it possible to adjust drying equipment quickly to new products and will reduce variations in product properties to a large extent.

ACKNOWLEDGEMENTS

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