INTRODUCTION

Spray drying is an essential unit operation for the manufacture of many products with specific powder properties. It is characterized by atomization of a solution or suspension into droplets, followed by subsequent drying of these droplets by evaporation of water or other solvents. Spray drying is used for the manufacture of many consumer and industrial products such as instant food products, laundry detergents, pharmaceuticals, ceramics and agrochemicals. The best known example of an instant food product is milk powder. Consumers desire a quick dissolution or dispersion of such powders in water or milk without the formation of lumps. But also manufacturers have their wishes. They require free flowing powders and absence of dust in such a way that it facilitates the handling of the powders. Both requirements are met by agglomeration of food powders [1,2,3].

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, see also Fig. 1. In this way the characteristics of a single particle are maintained while the bulk powder properties are improved by the creation of the larger agglomerates.

In a spray dryer agglomeration can take place within the spray of an atomizer, between sprays of various atomizers and between sprays and dry material being introduced into the drying chamber (e.g. by fines return, see Fig. 2). The latter technique is often the most effective way to achieve and control agglomeration in spray dryers.

Agglomeration takes place when two sticky particles, or a sticky and a dry particle, collide and form a liquid bridge that is strong enough to resist mechanical deformations, while the integrity of the particles is maintained. Various researchers have calculated the critical viscosity for sticking during contact times of a few seconds by applying various models. As a result the critical viscosity appears to be in the range of $10^6$ – $10^8$ Pa·s. This value has been confirmed experimentally by various investigators [4,5,6,7]. At lower viscosities the particles will coalesce upon collision, at higher viscosities the particles will not stick together (see also next chapter).

The critical viscosity occurs at a temperature that is called the sticky point temperature. Roos and Karel [8] related the sticky point temperature to the glass transition temperature which is characteristic for each material. For skim milk solids for example, the stickiness and caking zone is positioned at about 10 °C or higher above the $T_g$ measured by DSC [9,10]. Sticky points can further deviate from glass transition points, for instance because also the dynamics of colliding particles are also relevant. It would therefore be better to measure sticky points directly under dynamic conditions. However, the classical measurement techniques [11] are not very accurate and show poor reproducibility when the examined powder is not free-flowing. Sticky-point measurements and a novel approach to measure dynamic sticky-points based on attractor comparison methods are discussed in Verschueren et al. [12].
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 atomization process, the mixing of spray and hot air, the drying of suspension droplets and the collision of particles which might lead to coalescence or agglomeration. As a consequence, agglomeration during spray drying is operated by trial-and-error. In 2001 an EC-sponsored project started, coordinated by NIZO food research, entitled EDECAD (Efficient DEsign and Control of Agglomeration in spray Drying machines, www.edecad.com). The EDECAD project aimed at developing an industrially validated computer model, using computational fluid dynamics (CFD) technology, to predict agglomeration processes in spray drying machines. This paper presents some CFD simulation and validation results.

2. MODELLING SPRAY DRYING

Predictive computer models are helpful tools to maximize the production capacity of available installations, to minimize fouling of equipment and to reduce energy consumption. These models also reduce the number of costly and time-consuming production trials needed for the development of new products or processes. By Verdurmen et al. [13] an overview has been given how different modeling approaches can be applied to spray drying equipment. Currently, CFD is regarded as one of the best approaches to simulate spray drying process in detail [13,14,15,16,17,18,19]. The airflow field, the local temperature (see Fig. 4 as an example) and the local humidity (see Fig. 5 as an example) inside the spray dryer can be computed by using CFD techniques, taking into account the coupling for mass, momentum and energy.

The difference from standard (e.g. diesel sprays used in the automotive industry) spray calculations mainly concerns the drying part: stickiness primarily depends on the drying state of the outer layer of the particles. Additional sub-models for moisture diffusion inside the particles [18] and for the relation between the drying state and stickiness [10] are therefore required to be able to compute the drying and fouling behavior of spray drying systems.

Some powder properties (e.g. insolubility) can be related to the moisture content and the temperature-time history of the particles [21]. For these properties the modeling techniques described above can be used. The majority of relevant powder quality properties, however, are related to the degree of agglomeration.

The aim of the EDECAD project has been to develop an industrially validated CFD model, a so called Design Tool, to predict agglomeration processes in spray drying machines. The project has focused on agglomeration that takes place at the upper part of the spray chamber, i.e. between sprays and between sprays and fines return. The modelling technique used is an extension of the Euler-Lagrange model for the drying and fouling behaviour of spray dryers described above.

The initial spray conditions were measured and the sub-models for drying, collision and agglomeration were developed and validated by the academic partners in the project [22,23,24,25,26]. For a detailed description of the CFD model and its sub-models and pilot-plant validation work carried out by the industrial partners we refer to Verdurmen et al. [13].
3. RESULTS AND DISCUSSION

Fig. 6 shows a typical simulation result for the particle trajectories in the pilot plant dryer which was also used for the validation trials. The size of the particles shown in Fig. 6 is a measure for the particle diameter. The results clearly show that the smaller particles (fines) leave the dryer through the air outlet, whereas the majority of the larger particles leave the dryer through the bottom of the dryer. The results also show large recirculation pattern in the dryer, which is not unusual especially for relatively small particles.

Fig. 6. Simulated particle trajectories (the shown size is a measure of the particle diameter).

Fig. 7 shows the initial particle size distribution at the nozzle and the computed size distribution at the bottom of the dryer corresponding to the calculation shown in Fig. 6.

Two cases have been simulated: production of infant formulae without and with fines return. An increase in the particle size of the powder is observed when using a fines return configuration. This is in correspondence with experimental observations. In Table 1 the experimental and simulated average particle sizes are compared. It can be concluded that the simulations are giving results in the correct order of magnitude. However, there is still a need for further fine-tuning. Moreover, special attention has to be paid to experimental determination of model input parameters, especially to ones for which the model is sensitive such as viscosity and stickiness. In the current approach the sticky point, for instance, is assumed to be located at about 20°C above the glass transition line. There is some experimental evidence for that, but these results are not very accurate. The possibilities to measure stickiness more accurately are currently being investigated [12]. More accurate experimental results for stickiness will result in more accurate model results.

<table>
<thead>
<tr>
<th></th>
<th>Model prediction</th>
<th>Measured (directly at dryer)</th>
<th>Measured (after transport)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>without fines return</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>average diameter d (v, 0.5) [µm]</td>
<td>95</td>
<td>103</td>
<td>92</td>
</tr>
<tr>
<td>relative span [-]*</td>
<td>1.02</td>
<td>2.7</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>with fines return</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average diameter d (v, 0.5) [µm]</td>
<td>130</td>
<td>164</td>
<td>103</td>
</tr>
<tr>
<td>relative span [-]*</td>
<td>0.6</td>
<td>2.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>

* relative span is defined as (d (v, 0.9) – d (v, 0.1))/ d (v, 0.5)

4. CONCLUSIONS

The development of models for the food industry is an ongoing process. By choosing an approach as used in the EDECAD project, agglomeration in spray dryers can now also be simulated, although there is still a need for further fine-tuning. The resulting Design Tool establishes relations between process parameters, degree of agglomeration (e.g. particle size distribution, porosity) and final powder properties by combining information on material properties (e.g. sticky-point) and Computational Fluid Dynamics. This can be used by the industry for improved design and optimisation of spray drying and agglomeration equipment, to improve the quality of products and to increase the productivity of such equipment.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Hansen, P.S., Production of agglomerated fat-filled milk