Food drying as a challenge between process efficiency and product quality
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ABSTRACT
Food drying is a challenging process aiming at maximal efficiency under severe restrictions regarding the preservation of product quality. The present paper tries to give a brief overview of how the opposing requirements of fast processing and minimal product damage could be fulfilled simultaneously. Such solutions can be technological, by choice of the drying method to be used. This is explained by comparison of hot-air, vacuum contact and superheated steam drying. On the other hand, innovative solutions can be supported by new scientific approaches, illustrated by two examples. The first example concerns the use of population balance models, which provide access not only to the average values, but also to the distribution of properties relevant for dryer performance and product quality. The second example takes a further step to individual product entities, such as single droplets in a spray dryer. Computation of the change of state variables with the spatial coordinate in the droplet and with time provides the information on drying kinetics which is necessary to scale the process. And, it also provides the trajectories of exposure of sensitive ingredients that can deteriorate during processing. Possible paths for the transition from such discrete modelling to dryer design are outlined.

Keywords: Drying Droplet; Deactivation; Moisture Distribution; Crust Formation; Population Dynamics

INTRODUCTION
Drying of food is always subject to requirements on both, process efficiency and product quality. An efficient process would provide the energy necessary for evaporation of the water at high temperature, leading as fast as possible to low prescribed values of moisture content and water activity. Such harsh thermal conditions may be advantageous for some features of product quality (e.g. decontamination), but they damage the food by deactivation of important ingredients or by undesired phase transitions. The second aspect usually prevails, creating a dilemma between efficiency and quality inherent to the drying of food. This dilemma may be resolved either on a technological basis (by proper selection of drying methods and dryer types) or on a scientific basis (by application of modern modelling and measuring techniques). Both aspects are discussed in detail in recent books on drying technology [1], so that the present paper will only attempt a short and selective review. First, three common technological solutions for food processing (hot-air drying, vacuum contact drying, superheated steam drying) will be briefly outlined. Then, two scientific approaches which enable to resolve product quality features within a population of particles or even within single individuals of the population (such as single drying droplets) will be exemplarily discussed.

CHOICE OF TECHNOLOGY IN FOOD DRYING
The benchmark technology for the drying of food (and any other product) is hot-air drying (convective drying). Consequently, any other technology has to be placed and justified in terms of advantages by comparison to hot-air drying. One such technology commonly applied to food is vacuum contact drying. Whereas hot-air drying is by definition conducted in inert gas atmosphere, vacuum contact drying is carried out in an atmosphere of pure vapour (vapour of the liquid removed from the product, usually water). Since there is no inert gas that could provide the heat necessary for the evaporation of moisture in vacuum contact drying, this heat is supplied by contact with a hot equipment wall. The rational of vacuum contact drying is to keep the temperature of heat-sensitive products low and constant, at least as long as these products are still sufficiently wet. Wet materials have a relatively low temperature (the adiabatic saturation temperature) even when exposed to hot air. However, if the temperature of the air is increased in order to accelerate the process, then the temperature of the product also increases. On contrary, an acceleration of vacuum contact drying by increase of the temperature of the hot wall has no influence on the temperature of the wet product, because the latter is set by the selection of the operating pressure. In other words, process efficiency and product
quality are controlled by the same operating parameter (gas temperature) in hot-air drying, but by two different operating parameters (process rate by the wall temperature, product protection by the pressure) in vacuum contact drying. Freeze drying can be conducted by selecting pressures below the triple point. A further advantage of vacuum contact drying is that oxidative deterioration of the product and fire hazards can be avoided. Disadvantages concern equipment cost and the fact that an insulator (the already dried part of the product) is placed between heat source (hot wall) and heat consumption (evaporation front).

Superheated steam drying is similar to vacuum (or freeze) drying, because both processes take place under pure vapour atmosphere, do not involve gas phase diffusion, and are heat transfer controlled (Table 1). However, important differences also exist: At normal pressure the temperature of superheated steam drying is high, and heat input is by convection, not by conduction. The rational in comparison to hot-air drying usually is to reduce the energy consumption or to avoid oxidation and fire hazard. Conditions for heat recovery are favourable when using superheated steam instead of hot air because of the relatively high temperature level, the easiness of pure vapour condensation (no diffusion resistance, less temperature drop), and the possibility to either reuse the excess steam in the dryer after compression or utilize it externally.

Table 1. Main similarities and differences between superheated steam drying and vacuum/freeze contact drying

<table>
<thead>
<tr>
<th>Superheated steam drying</th>
<th>Vacuum / freeze contact drying</th>
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<tr>
<td>Pure vapour atmosphere, no diffusion</td>
<td>Heat transfer controlled</td>
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<tr>
<td>High temperature</td>
<td>Low temperature</td>
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<tr>
<td>Heat input by convection</td>
<td>Heat input by conduction</td>
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Advantages of superheated steam drying are: Higher drying rates than in hot-air drying due to liquid pumping by internal steam production, at temperatures above the so-called inversion temperature in the 1st drying period, and due to the absence of diffusion in the 2nd drying period; More porous structure of foods and vegetables, lower bulk density, and better rehydration, due to the internal production of steam; Less case-hardening (skin formation) than in hot-air drying; Pasteurization and sterilization, as well as better digestibility of feed, due to steam treatment and hydrolysis; Deodoration without odor emission in closed system; Stripping of acids that contribute to bitter taste; The possibility to convert any hot-air dryer for superheated steam use. The main disadvantage of superheated steam drying is that heat-sensitive products may be damaged by material temperatures of 100°C and more at normal pressure. This drawback can be relaxed by reducing the operating pressure, which leads to cross-over processes between superheated steam and vacuum drying. Further disadvantages of superheated steam drying are: High investment for ancillaries; More complex system involving hazards of leakage, condensation and air infiltration, as well as difficulties of start-up and shut-down; Loss of aroma; Accumulation of inert gases, condensable organics or dust in the steam recycle loop or in the condensate; Lack of desired oxidation (browning); Prolongation of drying time to heat up the material to the boiling point by steam condensation.

Further drying methods that come into question for food applications (such as atmospheric freeze drying, microwave vacuum or freeze drying, high-frequency drying, heat pump drying, zeolite drying or zeodration, supercritical drying) can be assessed upon their merits in terms of process efficiency and product quality in a similar way, based on dryer producer information, experience, expert opinions, and literature (e.g. [2]).

POPULATION DYNAMICS FOR DISTRIBUTED PRODUCT PROPERTIES

As previously pointed out, the choice of an adequate drying technology is of crucial importance for fulfilling partially contradictory requirements of process efficiency and product quality in food drying. Dryer-scale models can be used to support this choice. However, such models typically assume that every entity of the product (e.g. every particle) undergoes in the dryer the same evolution of moisture content and temperature as every other one. This does not correspond to reality in continuously operated dryers with a residence time distribution of the product, because particles that spend more or less time in such units than others can leave them over-dried or under-dried, and damaged.

To resolve relevant properties within the particle population, population balance modelling can be used. This approach has been applied systematically to drying in continuously operated, one-stage, well mixed fluidised beds [3-5]. The model consists of the following parts: 1) Population balance equations for the particle phase...
that distinguish between particles of different age and bring particle age into connection with moisture content and temperature; 2) The distribution of particle age, which is the residence time distribution of solids in the dryer; (in the described case an exponential decay function for one well-mixed vessel); 3) Separately determined single-particle drying kinetics in form of a product-specific normalised drying curve; 4) Mass and heat balances for the gas phase that account for changes along the height coordinate of the fluidised bed.

One result of this approach is depicted in Figure 1, left hand-side plot, as cumulative distribution of particle moisture content at the outlet of the dryer. We can see that the majority of particles (about 70%) leave the dryer with relatively low and narrowly distributed moisture contents. However, a strong minority (the remaining 30%) have higher moisture contents that cover the entire range up to the inlet moisture content of the solids in the respective experiments. Such distributions are nice for fundamental investigations, but they would be a disaster from the point of view of product quality in practice. This is why continuously operated fluidised bed dryers are not realised in form of a single vessel in practice, but in form of compartments in series or of lengthy rectangular constructions. Designs of this kind try to come close to plug flow behaviour of the solids. However, ideal plug flow can never be attained, so that the distribution of product properties will always be an issue. In connection with Figure 1 it should be noticed that the population balance approach requires numerical solution, but an analytical approximation is also possible after a number of simplifying assumptions [4]. To obtain the experimental distributions, it is necessary to measure the individual residual moisture content of a sufficiently large number of particles. This has been done by means of nuclear magnetic resonance [5]. Another important aspect is illustrated in Figure 1, right hand-side plot. Here, average values of outlet moisture contents calculated from the respective distributions are compared with values obtained under the assumption that the outlet moisture content is not distributed. The former correspond to the population balance approach, the latter to conventional dryer design models which are based on averages. We can see that there is a significant deviation in the results, which means that the assumption of equality of properties between particles does not only conceal the distribution of such properties, but it also falsifies the average, due to non-linearity of the drying process.

For the sake of simplicity, the results of Figure 1 were gained with ceramic particles (γ-alumina). It is, however, obvious that they are transferable to food particles – and more significant in that case, because elevated values of water activity do not damage the ceramics, but they do damage the foods. Furthermore, it is evident that the population balance approach can be expanded to consider, for example: Properties other than the residual moisture content or water activity, such as the retention of active ingredients; Formulation processes, such as spray fluidised bed coating or encapsulation; The entire range of axial dispersion conditions between well-mixed and plug-flow behaviour. Consequently, population balance modelling can be expected to foster understanding and the design of efficient drying processes for food in the future.

Figure 1. Moisture content of γ-alumina particles at the outlet of a continuously operated, lab-scale fluidised bed dryer [5]. Left: Comparison of measured cumulative distribution with predictions of the population balance model. Right: Average moisture content as a function of solids throughput.
DISCRETE APPROACHES TO PROCESS EFFICIENCY AND PRODUCT QUALITY

The previously presented population balance models enable to differentiate among groups of particles, but they are still smoothing out the profiles of state variables that evolve within each particle by the use of a normalised drying curve. However, the conversion of active ingredients contained in food particles by undesired reactions usually depends on the change of water content and temperature with time, so that this change should be spatially resolved for a more precise consideration. To achieve this, discrete approaches that refer to the single particle are necessary. In the example given here, the particle is a solidifying droplet, like any droplet flying through hot air in a spray dryer. It contains water that evaporates and a molecular, macromolecular or particulate solute that gives rise to the formation of the solid phase (for example, lactose). The highly diluted active ingredient (for example, an essential amino-acid) is considered to be evenly distributed in space, so that its loss can be treated as an add-on to the main droplet drying model. The latter has some similarities to recently communicated models [6, 7] and needs to be presented in more detail separately. For the purpose of the present discussion it is sufficient to point out its main characteristics, as follows:

- In a first period the droplet shrinks by gas-side controlled evaporation of water. Emerging profiles of solute concentration are computed by solving numerically the diffusion equation under moving boundary conditions.
- As soon as a critical concentration of solute is reached at the surface of the droplet, the formation of a solid crust begins, and the shrinking droplet is transformed to a drying particle of constant outer size. This so-called locking point marks the transition from the first to the second period of drying.
- The second period of drying is characterised by the inward propagation of a boundary that separates the dry crust from the still liquid core of the particle. Transport phenomena are treated in a quasi-stationary way in the crust, whereas the complete diffusion equation continues to be solved in the core.

Some exemplary results of the model are depicted in Figure 2. The top left plot shows the moisture distribution for five different points of time. The middle left diagram shows that outer diameter and liquid core diameter are identical and decrease during the first period of drying. In the second period, after the locking point, the outer diameter remains constant, whereas the diameter of the liquid core continues to shrink, which corresponds to an increase of the thickness of the crust. While the total amount of solids remains constant, the masses contained in the crust (or shell) and in the liquid core develop in opposing directions (top right plot). As illustrated in the middle right diagram, the average water content decreases continuously. The average moisture content of the liquid core remains on this curve until the locking point, but increases again afterwards. The reason for this behaviour is that the increasing mass transfer resistance of the crust slows down the drying process, so that concentration profiles in the liquid core have more time to move towards relaxation and equalisation by diffusion. Consequently, the difference between average moisture content in the liquid core and moisture content at the core boundary decreases in the course of the second period of drying and disappears asymptotically. The continuous decrease of evaporation rate with time shown in the bottom right plot is due to the decrease of surface area by shrinkage in the first period and to the increasing resistance of the crust in the second period. The bottom left plot illustrates the temporal evolution of the average porosity of the crust, as calculated from the mass balance of solids in the crust and the crust volume. The porosity increases with time, due to the already mentioned increase of water content (or decrease of solids content) at the boundary of the liquid core after the locking point. Finally, the results are summarised in the 3-D plot of Figure 2.

It should be stressed that the ratio between speed of diffusion (solute mobility) and speed of drying (drying rate) is of crucial importance for results like those of Figure 2, controlling both the spatial distribution and temporal evolution of state variables within the drying droplet, and the structure of the emerging solid particle. Model validation and/or the derivation of model parameters (such as the critical, locking point concentration) can be conducted with the help of experiments on single droplets suspended in an ultrasonic levitator. Post-process characterisation methods such as scanning electron microscopy (SEM) and x-rays micro-tomography can also be applied (see Figure 3).
Figure 2. Computed dynamics of drying and solidification of a liquid droplet, and the respective concentration profiles.

Though parameter identification and model validation need to be treated separately in more detail, it is evident that models of the discussed type that resolve the state variables in space and time provide a good basis for the reliable computation of deactivation of sensible ingredients. Two additional pieces of information are necessary to this purpose: First, separately measured deactivation kinetics for the ingredient under consideration (see, e.g., [8]) and, second, the air conditions to which the droplet is subjected in a real dryer. The latter can be gained in case of a spray dryer by computational fluid dynamics. Theoretically, the complete single droplet model, including the deactivation add-on, could be used for every droplet in the
tower. In practical terms however, it is difficult and computationally very expensive to insert a single-
individual model that requires numerical integration in a genuine discrete particle approach. This difficulty
might be overcome by model reduction, either by first reducing the drying model to an analytically solvable
version (e.g. a retreating front model) and then adding the kinetics of deactivation, or by first adding
deactivation and then reducing to analytical expressions for both drying kinetics and active ingredient loss by
application of, e.g., the so-called reaction engineering approach [9]. Hereby, the higher-order model is used
to derive the parameters of the lower-order one. This would save experimental effort and account for the fact
that drying tower conditions cannot be fully depicted in small scale experiments (levitator). In any case, a
huge potential appears to exist towards efficient processing of perishable goods, especially food materials.

Figure 3. Water-lactose droplet observed during the drying in an acoustic levitator (left), after the drying by SEM
(middle), and after the drying by x-rays micro-tomography (right).

CONCLUSIONS

Drying is a step of food processing that should be conducted in a gentle but efficient way. This can be
achieved by the educated selection of technologies and dryer types. On the other hand, it can be supported by
modern computational techniques such as population balance or discrete particle modelling. Population
balances can be used to calculate the distribution of product properties (for example water activity) at the
outlet of continuously operated dryers such as fluidised beds. Models for the drying and solidification of
single droplets can help to, e.g., avoid the loss of active ingredients during spray drying of dairy products.

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