Spray dryers are being used in many industrial areas for converting a liquid suspension or solution into a dry powder. Essential for further processing or use are the properties of the powder which are of course determined by the operational conditions for spray dryers. The particle-laden flow in a spray dryer is very complex and numerous transport processes and physical effect influence droplet motion and drying history, eventually affecting the powder properties. Most dryers are operated in a co-current configuration where both hot air and liquid spray are injected from the top of the dryer and the powder product is extracted at the bottom.

Consequently, the powder properties are influenced by:

- The inlet air flow velocity and temperature.
- The inlet flow structure, i.e. mostly swirl is imposed for establishing a certain flow structure within the dryer and hence yielding a certain residence time of the droplets.
- The atomisation of the liquid (i.e. suspension or solution) which is realized by rotary or nozzle atomisers. Besides the operational conditions the initial droplet size distribution is affected by the liquid properties such as viscosity and surface tension, which are correlated with the solids content.
- Droplet path through the dryer and resulting experienced temperature history. This largely influences the drying process of the droplets and hence the resulting dried particle shape and inner structure.
- Collisions between droplets among one another, which mainly occur in the vicinity of the atomizer; collisions between droplets and particles happening due to recirculating of residual dried particles; as well as collisions between more or less dried solid particles. All these collisions will yield coalescence, satellite droplets or agglomerates and eventually influence the powder properties (e.g. size distribution).
Figure: Summary of modelling requirements for the numerical calculation of spray dryers.

This summary shows the extreme complexity of a spray drying process which of course has big consequences for the design, specification of operational conditions and optimisation of spray dryers. Therefore, mostly experimental approaches utilising pilot-scale plants are being used for these purposes. Since about 20 years, however, numerical approaches based on CFD (computational fluid dynamics) are increasingly applied for dryer design and optimization.
(see e.g. Langrish and Zbicinski 1994; Huang et al. 2004 and 2006; Woo et al. 2010; Blei and Sommerfeld 2007; Anandharamakrishnan 2013). For a coupled calculation of air flow and droplet/particle motion generally the Euler/Lagrange approach is applied due to the important requirement in predicting the droplet size distribution and the droplet size change due to drying. This method implies that the fluid flow is calculated on a fixed Eulerian grid based on the time-averaged conservation equations (termed as RANS equation) and using an appropriate turbulence model (see figure). Furthermore, the influence of droplets and particles on the fluid flow needs to be accounted for through source terms in the conservation equations. For capturing the generally asymmetric flow structure evolving in a spray dryer the simulations should be done three-dimensional (Mezhericher et al. 2009) and also, if the computational resources allow, in a transient way, because a swirling air jet will result in a precession of the flow pattern (Fletcher et al. 2006; Woo et al. 2010). Different RANS-type turbulence models were analysed by Huang et al. (2004) with the conclusion that a RNG-k-ε turbulence model gives adequate results with reasonable computational times. Large-eddy simulations (LES) of spray dryers are still rare due to the high computational burden.

For simulating a spray with the Lagrangian approach requires the application of the parcel concept as the real number of droplets in a spray dryer is huge and cannot be captured by numerical simulations today. Therefore, particles are grouped together in parcels which are numerically tracked and considered as point-masses. The particles in one parcel have the same properties such as size, velocity, temperature and fluid properties in the case of droplets. When moving through the flow all particles in the parcel behave in the same way.

Modelling the behaviour of droplet/particle motion through spray dryers requires a huge number of sub-models (see figure) for capturing all physical transport effects influencing the performance of the dryer and predicting particle properties reliably. First the modelling of liquid atomization (often referred to as primary break-up) is rather sophisticated and no generalised models are available so far (Yoon 2010). For pressure nozzles the so-called blob model may be applied where the initial droplets are injected with the diameter of the nozzle hole and then are allowed to further break-up (called secondary break-up) due to fluid dynamic forces. For that several models are available which were examined in detail by Kumzerova et al. (2007). Another approach to describe the size distribution of injected droplets is based on measurements (see e.g. Rüger et al. 2000), which are being performed a
few millimetre downstream of the nozzle at several radial positions. These local size
distributions and the local liquid mass flux as well as the size-velocity correlations are used to
randomly create new injected droplet parcels each time step of parcel tracking.

The next important issue in tracking droplets or particles are the fluid dynam ic forces being
relevant to be considered. In any case drag and gravity are the most important forces. The
pressure force, added mass and Basset force may be neglected in a gas-particle flow due to the
large density ratio (Sommerfeld et al. 2008 a; Crowe et al. 2012). However, transverse lift
forces due to shear and particle rotation need further consideration as they become important
if the particles are larger, i.e. \( d_p > 50 \mu\text{m} \) (Sommerfeld 2010).

Essential for respecting the influence of turbulence on droplet motion is the generation of the
instantaneous fluid velocity seen by the particles. This may be realized by different more or
less sophisticated models, namely, the simple eddy-lifetime model (Gosman and Ioannides
1983), a single step Langevin model (Sommerfeld et al. 1993) and a full Langevin model
(Minier 1999), see also Lipowsky and Sommerfeld (2005) and Sommerfeld et al. (2008 a).

For describing the drying behaviour of the droplets numerous models are available (see Farid
2003; Sano and Keey 1982 and Nesic and Vodnik 1991). However, in these models some
simplifications were made whereby model calculations do not fully match experimental
findings, e.g. regarding the temporal evolution of the droplet temperature (Darvan and
Sommerfeld 2014). Therefore, a more comprehensive model was developed also accounting
for the diffusion of solid particles within the droplet (i.e. giving a solids concentration
distribution within the droplet) and the distribution of the droplet internal temperature
(Darvan and Sommerfeld 2014). Results for various drying scenarios will be introduced.

Furthermore, the modelling of droplet or particle collisions in a spray dryer is very important
since they have a direct influence on the powder properties (Sommerfeld et al. 2008 b). However, due to droplet drying their physical properties (e.g. viscosity and surface tension)
are strongly varying throughout the dryer and consequently also the collision behaviour and
the outcome of collisions. It may be distinguished between the following four types of
collisions (Blei and Sommerfeld 2006, 2007):
• between surface tension dominated droplets having rather high viscosity (consider suspensions or solutions), which mainly occur in the vicinity of the atomizer and result in either bouncing, coalescence or separation (see Kuschel and Sommerfeld 2013). A new model for describing such collisions developed by Sommerfeld and Kuschel (2013) will be briefly introduced.

• between viscosity dominated droplets (i.e. partially dried droplets with very high viscosity larger than about 1 Pa-s) yielding partial or full penetration or even a full passage. It should be noted that most probably the two colliding droplets have different viscosity and size in a spray dryer. This type of collision may form structured agglomerates (Blei and Sommerfeld 2007; Sommerfeld and Stübing 2012).

• between dry particles and droplets which also involves penetration and may yield structured agglomerates.

• between dry particles which may result in rebound or agglomerate formation due to van der Waals forces; i.e. rather weak agglomerates are formed (see Ho and Sommerfeld 2002).

Naturally, the occurrence of agglomerates also results in a scenario where primary droplets/particles collide with agglomerates. Then of course a reduced impact efficiency (i.e. a small particle might move around a large particle or agglomerate with the relative flow) should be accounted for (Ho and Sommerfeld 2002). Particle collision models mostly assume that in the case of agglomeration the new particle has the volume equivalent diameter. This is of course for structured agglomerates not correct since for example the diameter of an enwrapping sphere is much larger. Hence, an agglomerate may be assumed to be represented by such a sphere having however a certain porosity. This of course will yield a different fluid drag compared to a volume equivalent sphere (Dietzel and Sommerfeld 2013).

In order to allow the consideration of the effective agglomerate size a statistically based agglomerate structure model was developed by storing the location of all primary particles within the agglomerate for each Lagrangian agglomerate still considered as point-mass. The collision partner (i.e. primary particle incorporated in the agglomerate) for a new primary particle is found by a random process considering the “real” dimension of the agglomerate. Thereby also the correct collision cross-section of the agglomerate is respected (Sommerfeld and Stübing 2012). Model simulations with this new structure model will be introduced.
Finally, first simulations of a pilot-scale spray dryer are introduced using the agglomeration model and the novel drying model.

References


