



Research article

Coupled Eulerian-Lagrangian simulation of spray-drying skimmed milk powder

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Abstract

Importance of the work: Drying skim milk powder is a complex process dependent on the drying temperature, airflow and residence time distribution in the spray dryer. Stickiness can impact production.

Objectives: To simulate the movement of particles within the spray dryer, and account for the observed stickiness of the skimmed milk powder.

Materials & Methods: 1) The model was validated using available published data to determine model accuracy. 2) The model was used for airflow pattern prediction. 3) The particle residence time was predicted. 4) The stickiness was predicted in the context of the spray drying process. 5) The final component simulated the spray drying process itself.

Results: A three-dimensional CFD simulation was performed for a co-current pilot plant spray dryer using a pressure nozzle for the purpose of spray drying skimmed milk powder. The simulated data agreed with published experimental findings, suggesting that the CFD simulations provided accurate predictions of the activity inside the spray dryer. The airflow comprised a core that flowed at high speed, with a slower zone of recirculation around the core. The particle trajectories depended upon the airflow patterns, resulting in the residence time of the smaller particles exceeding that of the larger particles. The deposits resulting from stickiness were typically on the walls of the conical section.

Main finding: Stickiness arises during the process of spray drying, and this is important because it is a quality that can be utilized in controlling the potential enlargement of the particles. This can lead to better-quality powder.

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Introduction

The production of milk powder involves the evaporation of water from milk, resulting in a dairy product comprising protein, fat and lactose (Fialho et al., 2019). This form of milk is more compact and thus can be readily transported. The most widely used forms of milk powder are whole milk powder (WMP), skimmed milk powder (SMP) and milk protein concentrate (MPC), according to Singh et al. (2019). These various milk powders are ingredients found in snacks, soups, bakery products, confectionaries, chocolate, ice creams, various drinks and recombined milk (Agarwal et al., 2015).

Most milk powder production is carried out using spray drying technology, which is able to create dry powders from liquids by quickly drying droplets of milk using hot air (Tamime, 2009). Materials that are sensitive to heat, such as foods and pharmaceutical goods, can benefit from this drying technique. Furthermore, this approach can serve as an alternative means of crystallizing amorphous powders when drying is carried out, as a consequence of the effects of temperature on amorphous powders (Auamwong and Srinophakun, 2020).

The spray drying process allows droplets of liquid to be converted to a dry powder using directed hot air. The droplet temperature is maintained at a relatively low level because the evaporation takes place very quickly; therefore, very hot air can be used without damaging the powder and creating a poor-quality product (Roustapour et al., 2009). Stickiness is one problem that often arises during the process of spray drying involving milk powder. To understand this issue better, analyzing a model of the agglomeration process during spray drying is helpful. This research examined the heat and mass transfer of the droplets using the Discrete Phase Model (DPM) alongside Computational Fluid Dynamics (CFD) to explain patterns of airflow, particle residence times and the skimmed milk powder stickiness when the process of spray drying takes place (Alwan and Binder, 2019).

The method can be applied to similar phenomena and uses computer simulations (Versteeg and Malalasekera, 1995). There are three principles which underpin all fluid flow calculations. The first is conservation of mass, the second is conservation of energy and the third is adherence to Newton's second law. Mathematical equations that follow these principles can be constructed. The Navier-Stokes set of equations can encompass the various processes of heat, momentum and mass transfer. These are a set of partial differential equations (Toledo et al., 2007). At the same time, it is not possible to solve these equations to produce a general analytical solution,

a discrete numerical solution can be obtained. Typically, the CFD approach divides the flow region into a very large quantity of cells, followed by developing discrete partial differential equations. The finite volume method is the most commonly used (Langrish et al., 2020; Surono et al., 2023).

This study examined the model of spray drying in order to make better predictions of how the internal conditions in the spray dryer will affect milk powder when considering the heated region and the transfer of mass from the central core toward the outer regions of the chamber in the dryer. This work separated the model into four sections: 1) validation of the model accuracy using the data obtained experimentally by Kieviet and Kerkhof (1997); 2) prediction of the flow of the air; 3) prediction of the particle residence time distribution; and 4) prediction of how stickiness would arise during the process of spray drying.

Material and Methods

Formulation of spray drying model for prediction stickiness during spray drying

A combination of the Eulerian and Lagrangian models was used to simulate spray drying to determine the particle trajectories through the solution based on the force balance as shown in Equation 1:

$$\frac{d\mathbf{u}_p}{dt} = \frac{18\mu}{\rho_p d_p} \frac{C_D Re}{24\nu \mathbf{u}_p g \left[\frac{\rho_p - \rho_g}{\rho_p} \right]} \quad (1)$$

where, $\mathbf{v}$ is the fluid phase velocity, $\mathbf{u}_p$ is the particle velocity, ρ_g is the density of the fluid and ρ_p is the density of the particle.

The equation of motion, or particle force balance, takes into consideration gravity, aerodynamic drag and discrete phase inertia. The slip Reynolds number (Re) and drag coefficient (C_D) were calculated using Equations 2 and 3, respectively:

$$Re = \frac{\rho_g d_p |\mathbf{u}_p - \mathbf{v}|}{\mu} \quad (2)$$

$$C_D = a_1 + \frac{a_2}{Re^{a_3}} \quad (3)$$

where d_p is the particle diameter and a_1 , a_2 and a_3 are constants that apply to smooth spherical particles over several ranges of Reynolds number (Re).

The values for the heat and mass transfer between a hot gas and particles was derived using Equation 4 following the particle motion:

$$m_p c_p \frac{dT_p}{dt} = h A_p (T_g - T_p) + \frac{dm_p}{dt} h_{fg} \quad (4)$$

where, m_p is the mass of the particle, C_p is the particle heat capacity, T_p is the particle temperature, h_{fg} is the latent heat, A_p is the surface area of the particle and h is the heat transfer coefficient.

The heat transfer coefficient (h) was obtained from the Ranze-Marshall equation (Equation 5):

$$Nu = \frac{h d_p}{k_{ta}} = 2 + 0.6(Re_d)^{1/2} (Pr)^{1/3} \quad (5)$$

where, the Prandtl number (Pr) is defined using Equation 6:

$$Pr = \frac{c_p \mu}{k_{ta}} \quad (6)$$

where, k_{ta} is the thermal conductivity of the fluid and μ is the molecular viscosity of the fluid.

The evaporation mass transfer rate between gas and particles was determined using Equation 7:

$$\frac{dm_p}{dt} = k_c A_p (Y_s - Y_g) \quad (7)$$

where, Y_s is the saturation humidity, Y_g is the gas humidity and k_c is the mass transfer coefficient that it can be obtained from Sherwood number (Equation 8):

$$Sh = \frac{k_c d_p}{D_{i,m}} = 2 + 0.6(Re_d)^{1/2} (Sc)^{1/3} \quad (8)$$

where, $D_{i,m}$ is the diffusion coefficient of water vapor in the gas phase and Sc is the Schmidt number, defined using Equation 9:

$$Sc = \frac{\mu}{\rho_g D_{i,m}} \quad (9)$$

The literature provides various sources for coefficients of density, vapor pressure, diffusion, and specific heat. After the droplet temperatures reach their boiling point, and the droplet mass is greater than that of the non-volatile fraction, the model for the boiling rate is provided by Equation 10:

$$\frac{d(d_p)}{dt} = \frac{4k_{ta}}{\rho_p c_g d_p} \left(1 + 0.23\sqrt{Re} \right) \ln \left[1 + \frac{c_g (T_g - T_p)}{h_{fg}} \right] \quad (10)$$

where k_{ta} is the thermal conductivity of the gas and c_g is the heat capacity of the gas. These equations were provided and used as computational algorithms in CFD.

Simulation geometry generation and mesh generation

Fig. 1 shows the design of the geometry for the study simulation completed using the SOLID WORK software (<https://www.solidworks.com/>). The same chamber dimensions and dimensions of the air inlet were selected as those used in the experiments of Kieviet and Kerkhof (1997). The height was 3.7 m, and the diameter was 2.2 m. The cyclone separator was added as a component positioned at the top of the chamber which removed particles from the air. The hot air passed through an annulus to enter the chamber from the top and was taken out via piping from the conical section of the chamber.

Fig. 1B presents the simulation mesh geometry created using the ANSYS WORKBENCH software version 12.1 (<https://www.ansys.com/>) with a 3.4 GHz central processing unit and 8 GB of random-access memory. The number of grids in Fig. 1B was 185,000 that produced an unstructured mesh, while the grid type was a triangular mesh. Details on the conditions, properties and assumptions are provided in Tables 1 and 2.

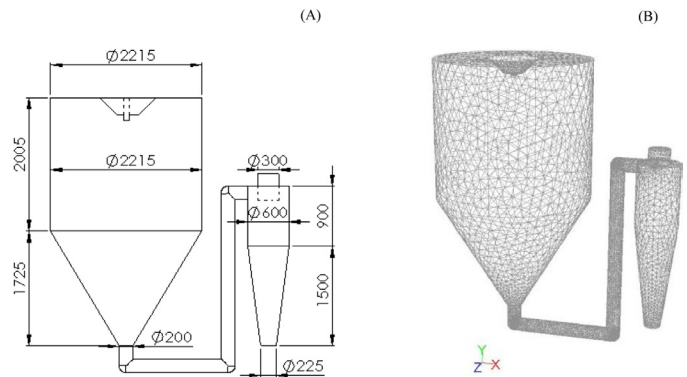


Fig. 1 (A) Spray drying process design; (B) spray drying process simulation mesh geometry, with all measurements in millimeters

Table 1 Boundary conditions used for simulation.

Property	Value
Air mass flow rate (kg/s)	0.336
Air temperature (K)	468
Air velocity (m/s)	7.36
Spray flow rate (kg/s)	0.0139
Spray cone angle (degree)	76
Velocity at the nozzle (m/s)	59
Feed temperature (K)	300
Turbulence k - value (m^2/s^2)	0.027
Turbulence ϵ - value (m^3/m^2)	0.37
Pressure at an outlet (Pa)	-100
Chamber wall thickness (m)	0.002
Wall material	Steel
Wall-heat transfer coefficient (W/m^2K)	3.5
Interaction Boundary Conditions between wall and droplet	Reflect
Spray of droplets assumed to be a solid (%)	42.5

Table 2 Skim milk powder properties

Property	Value
Density (kg/m ³)	1,549
C _p Specific heat (J/kg-K)	1,790
Thermal conductivity (W/m-K)	0.03356
Viscosity (poise)	0.0179
Latent heat (J/kg)	2,277,000
Boiling point (K)	373
Mass diffusivity (m ² /s) Chen et al., 1999	270,000
Saturation vapor pressure (Pa)	93,289
Droplet surface tension (N/m) sourced from McCarthy (2002)	0.04729

The assumptions were:

1. The spray drying chamber is a cylinder-on-cone.
2. Droplet sprayed from pressure nozzle atomization has a hollow cone spray pattern.
3. The airflow pattern inside the spray drying chamber is co-current.
4. Heat and mass transfer of the droplet come from the drying kinetics for a single droplet.
5. No hygroscopic capillary-porous media in a spherical shape for the particles.
7. Physical properties, such as thermal conductivity, density and viscosity of the gas, mass diffusivity and heat capacity of the particle, are constant.
8. Agglomerated powders still have the same spherical shape.
9. The effect of gravity force is considered.
10. The effect of droplet-droplet interaction is considered.

Results and Discussion

The results can be separated into five parts: 1) validation of the model using the data provided by Kieviet and Kerkhof (1997) to determine model accuracy; 2) airflow pattern prediction; 3) particle residence time prediction; 4) stickiness prediction in the context of the spray drying process; and 5) the spray drying process itself.

Spray drying model validation.

Three-dimensional CFD simulation was used to present the air velocity and air temperature profiles for the spray drying chamber.

Profile of air velocity

When the CFD simulation was carried out to model the profile of air velocity in the absence of spray in the dryer,

it was apparent that the flow field comprised a rapidly flowing downward core, while slow recirculation occurred around the upper section of the core close to the conical section of the chamber, as can be observed in Fig. 2A. The core became wider as it progressed downward to the outlet. The central core in this study had a radius of around 0.2 m. The rapid decline in the velocity at the chamber axis reduced as the air dropped into the conical section of the chamber. Three grid resolutions (80,000, 120,000 and 160,000) were used for the representation of the findings. The findings from the simulation indicated that there were some error values within the acceptable criteria for the 120,000 grids, while the calculations could be completed using the Fluent software within a shorter timespan than was the case for the 160,000 grids. For this reason, the results shown in this study are those for the 120,000 grids.

Figs. 2B–2D present different profiles for the velocity inside the chamber to draw comparisons between the simulation values and the experimental data from Kieviet and Kerkhof (1997) in the absence of spray. There was a good level of agreement, especially when taking into account the measurement results and the process complexity. The velocity distribution in the core of the chamber was non-uniform, while the greatest velocity recorded was 7.36 m/s at 0.30 m from the ceiling. The velocity was reduced when the air streamed within the chamber moving downward, in a trend that closely matched the results from the experiments.

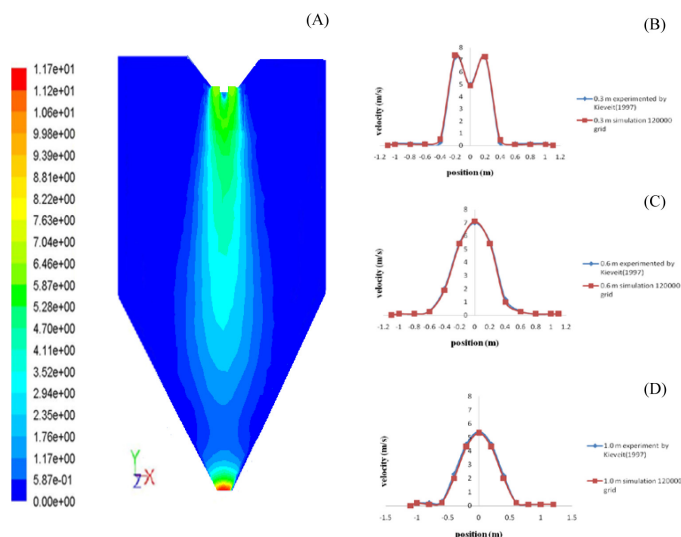


Fig. 2 (A) Air velocity profile (meters per second) in spraying chamber; (B) profile at 0.3 m; (C) profile at 0.6 m; (D) profile at 1.0 m, where validation of simulation was based on experimental data from Kieviet and Kerkhof (1997)

However, the velocity magnitude prediction for the 1.0 m level exceeded the experimental values, which may have resulted from periodicity in the airflow velocity magnitude at different positions within the chamber, with the 1.0 m level being one such affected position. This particular aspect of the air flow was mentioned by Kieviet and Kerkhof (1997) when velocities were measured in these various locations. Thus, it could be inferred that air flow within the spray dryer had a transient nature and therefore a transient CFD model was necessary to simulate this phenomenon.

Air temperature profile

The air temperature profile simulation in the absence of spray in the spray dryer is presented in Fig. 3A, in which the pressure nozzle has no spray. The simulated air temperature profile was compared with the experimental data from Kieviet and Kerkhof (1997) and the results for the different levels can be seen in Figs. 3B–D. The predictions were in good agreement with the experimental findings.

In Fig. 3A, the profile for the air temperature indicates that for the central core region with a diameter of 2.2 m, the temperature differed substantially at the levels of 0.3, 0.6 and 1.4 m. The rapid fall in temperature seen at the chamber axis decreased when the air passed down into the conical section of the chamber, while the predicted temperatures for the 0.3, 0.6 and 1.4 m levels exceeded the measured results. The difference was due to periodicity in the temperature in different positions within the chamber when the measurements were taken. From this, it could be inferred that the airflow in the plant dryer was transient.

Air velocity vector

Figs. 4A and 4B show the velocity vector plots for the airflow inside the chamber and the velocity streamline for the airflow inside the chamber, respectively. At the inlet, there was

only an axial velocity component for the airflow. The flow field had a core flow zone of high velocity while the core was a slow recirculation zone. The core flow then extended to the outlet of the chamber, creating a vortex flow close to the cylinder junction with the cone. The vortex flow extended upward around the core flow inside the chamber. The flight paths taken by particles were determined in part by the air flow patterns and to a certain extent by the drying rates. The reason for performing discrete phase droplet or particle modeling is to be able to simulate the paths of particles inside the dryer, indicating particle residence times, as well as any deposition of particles on the dryer walls.

The wall provided no heat transfer and there was consistency within the system with the outside wall temperature, which was maintained at a constant 300 K (Fig. 4C). The overall flow of the air temperature inside the chamber was considered by the system. It can be seen that heat was steadily transferred over time from areas of high temperature to areas of low temperature.

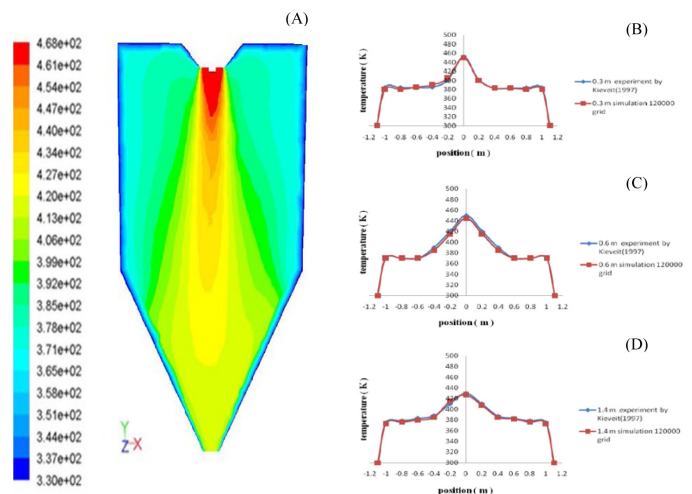


Fig. 3 (A) Air temperature profile (in degrees Kelvin) in spraying chamber; (B) profile at 0.3 m; (C) profile at 0.6 m; (D) profile at 1.0 m, where validation of simulation was based on experimental data from Kieviet and Kerkhof (1997)

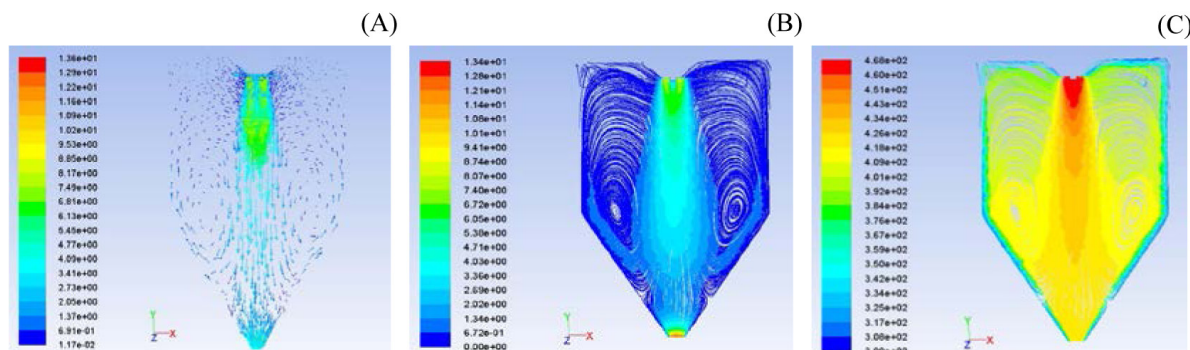


Fig. 4 Profiles for air velocity (meters per second): (A) vector plot; (B) streamline; (C) streamline depiction of air temperatures in degrees Kelvin.

Distributions of particle residence times

A parametric study was performed to evaluate the distribution of particle residence times for skimmed milk powder undergoing drying in the chamber. The key parameters were the diameter of the droplets (40, 70, 100 μm) and the air temperature at the inlet (433, 468 K). The model used a pressure nozzle with a hollow cone spray pattern and continuous spraying of droplets. The particle residence time refers to the length of time the particles remain inside the drying chamber, measured from the moment they leave the nozzle until they

reach the chamber exit. Fig. 5 presents the mean residence times predicted for droplets of differing diameters, while Fig. 6 shows the mean residence time predictions for the two different air temperatures at the inlet. The diameter of the droplets affected the mean residence time of the particles. The tests were carried out in triplicate to estimate the mean residence times in the context of droplet diameter. The findings clarified that the mean droplet diameter had a substantial influence on the residence time. The model relied upon the patterns of airflow within the dryer and the effects of gravity. An incremental rise in the mean droplet size led to a reduction in the residence time,

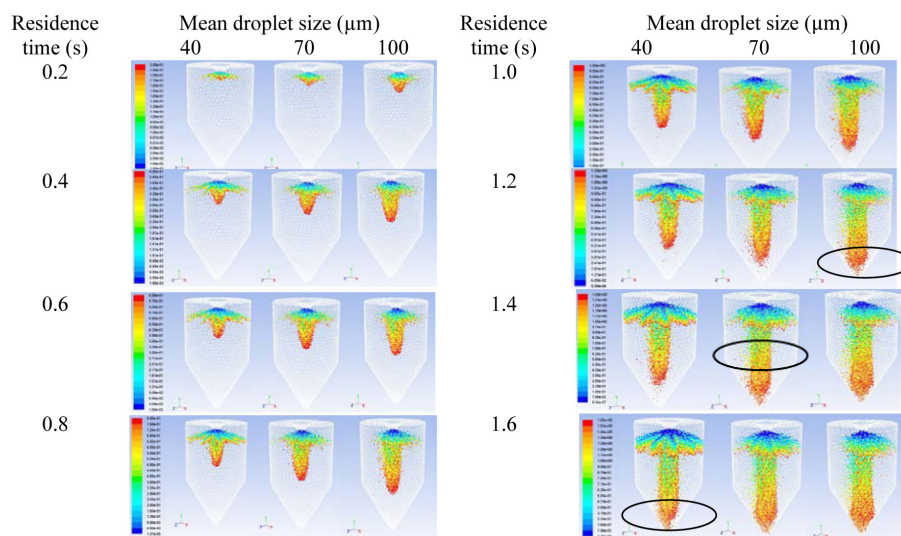


Fig. 5 Particle residence time versus Mean droplet size

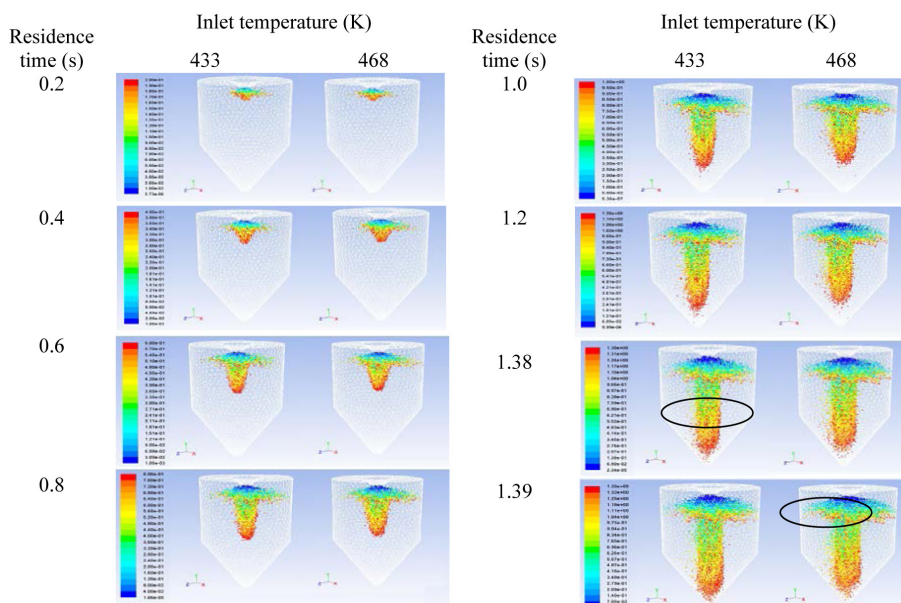


Fig. 6 Mean residence time versus two different inlet temperature

since smaller droplets lacked the momentum to leave the core flow; instead, they were pulled into the pattern of the airflow. Larger droplets fell due to gravity, resulting in larger particles having lower residence times. For example, with sizes of

40, 70 and 100 μm , the respective mean residence times were 1.6, 1.4 and 1.2 s, confirming the findings of Omid et al. (2009).

In the simulated system, the velocity of the inlet air and injection could be fixed at a constant level, while particles of 40, 70 and 100 μm underwent testing to determine the influence of particle sizes upon the extent of any stickiness, as well as the overall residence time within the drying chamber. Particles spending a long time in the spray drying chamber were indicated in red, while blue represented particles that first entered the drying chamber. The distribution of particles at 0.2 s indicated that because of gravity, large particles tended to settle faster than smaller particles.

The influence of air temperature at the inlet on the mean residence time of the particles can be seen in Fig 5. For example, using 70 μm as the mean diameter of the droplets, at temperatures of 433 and 468 K, the mean residence times were 1.38 and 1.39 s, respectively (Fig. 6). There was no substantial difference between mean residence times for the two different temperatures at the inlet. The system fixed the air velocity at the inlet and the injection velocity as constants,

while observations were made when the particle size used was 70 μm . The resulting mean residence times for the particles at the two different temperatures for inlet air indicated that the particles colored red spent a long time in the spray drying chamber, blue particles were the first to enter the drying chamber. According to Fig. 6, the particle distribution period was in the range 0.2–1.39 s.

Spray drying model stickiness.

CFD can be used alongside the simulation of skimmed milk spray drying in order to obtain a prediction of the stickiness, which is a commonly observed phenomenon during the drying process. Three different droplet sizes were tested (40 μm , 70 μm , 100 μm). Stickiness also depends upon air humidity and temperature. Figs. 7A and 7B show the fluid simulation results based on the simulation using the Fluent software. The heat and mass transfer equations showed that droplets of size 40 μm had a greater surface area and thus greater heat and mass transfer than the larger droplets, which was consistent with the findings of Master (1985), who reported the temperature profile of 40 μm particles generated superior heat transfer results. In addition, these findings also matched the humidity profile for the droplets of 40 μm , which provided good mass transfer.

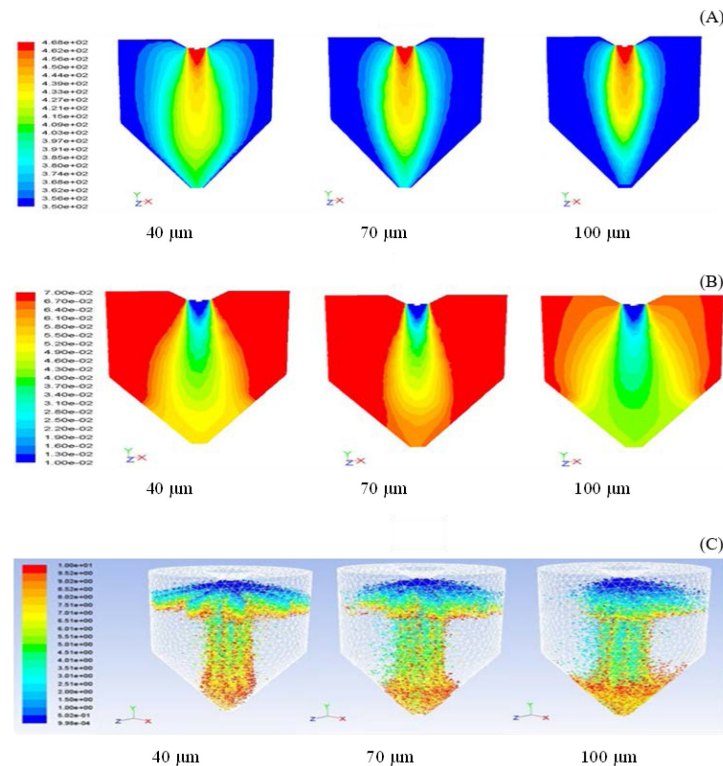


Fig. 7 Particle residence times (seconds) in chamber, based on spray drying model for three different droplet sizes (40 μm , 70 μm , 100 μm): (A) temperature profile; (B) moisture content profile; (C) stickiness profile.

Fig. 7C shows the particle residence times within the chamber for spray drying with injections at 10 s intervals for particle sizes of 40 μm , 70 μm and 100 μm , respectively. The red particles spent a long time in the spray drying chamber, while blue particles were the first to enter the drying chamber. Larger particles (100 μm) were able to penetrate the fast-flowing core to reach the zone of slow recirculation, while smaller particles were unable to make such progress. Primarily, stickiness results in depositions appearing on the conical wall, while much smaller deposits might sometimes be seen on the cylindrical chamber wall. Incremental increases in droplet size led to increases in stickiness, since larger particles are associated with greater humidity, which in turn increases stickiness.

Spray drying process and plant design.

CFD simulation of the skimmed milk spray drying process was used to inform the design of the drying plant. The separation of particles from the high velocity flow can be achieved through the installation of a cyclone. The simulation of the spray drying process is illustrated in Figure 8 based on the residence time, where the air entrance is in a high position, while the exit velocity from the air chamber was also high. Therefore, the air flowed to the cyclone through the pipe, indicating a very high speed in the elbow as a result of angular velocity. This allowed the particles to be separated from the air, with the center used under the centrifugal principle. Due to gravity, the larger particles fell, whereas the much lighter ones were able to pass out above the cyclone.

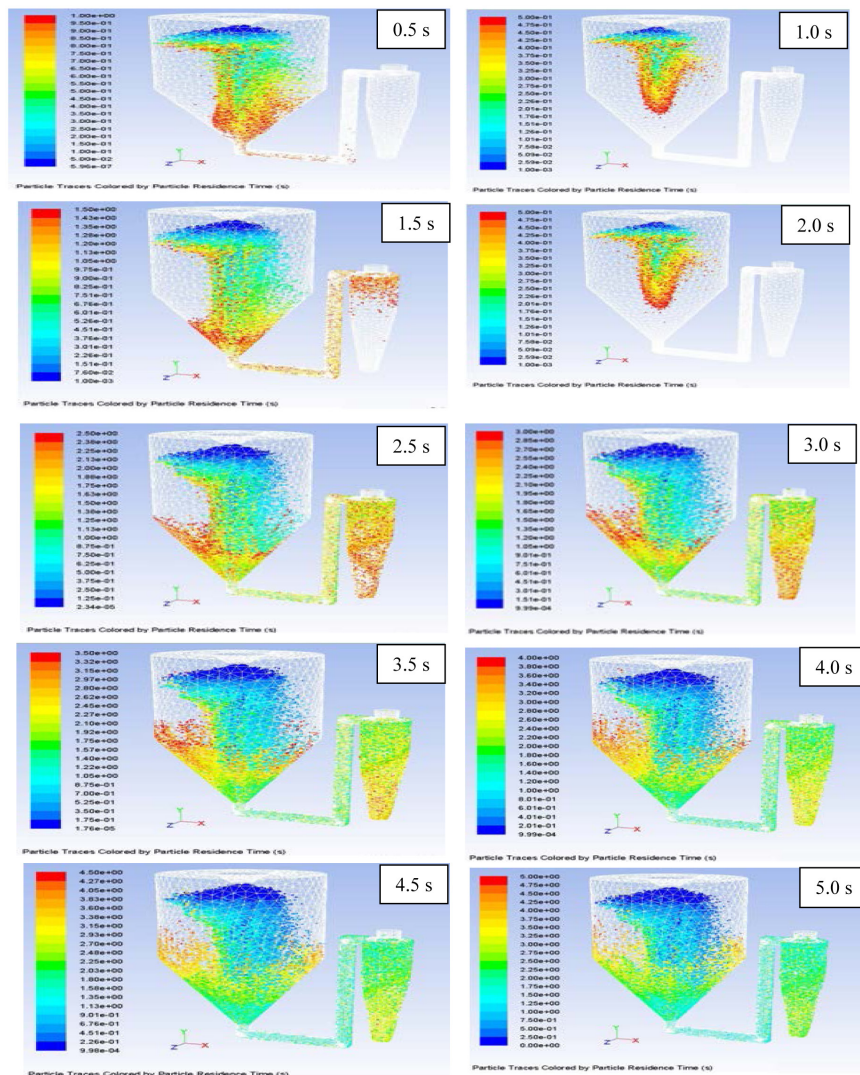


Fig. 8 Particle residence time (seconds) in spray drying process for different drying intervals (0–5 s in 0.5 s intervals)

Fig. 8 presents the particle residence time during spray drying at intervals of 0.5 s for a total of 5 s. It can be seen that the particles begin to dry out at around 3 s and can then be separated from the air flow. These findings matched those reported by Master (1987).

The spray dryer system was simulated, following a design that matched the one common applied in industry (Fig. 9), with an outlet pipe connecting the spray dryer and a cyclone. A majority of the particles which are sprayed dropped to the bottom under gravity, while lighter particles had a chance to escape the dryer into the cyclone. The spray dryer had a function of trapping the lighter particles. Inside the cyclone, the in feed met the tangential velocity, whereupon the swirling effect resulting from the centrifugal force deposited material on the walls. Larger particles were pulled towards the cyclone underflow. The transient simulation of the spray dryer occurred at 3 s. Stickiness might lead to a loss of milk production in the cyclone, because sticky milk particles could be deposited on the wall of the cyclone. When excessive quantities of milk adhere to the wall, it is necessary to halt the process to carry out maintenance.

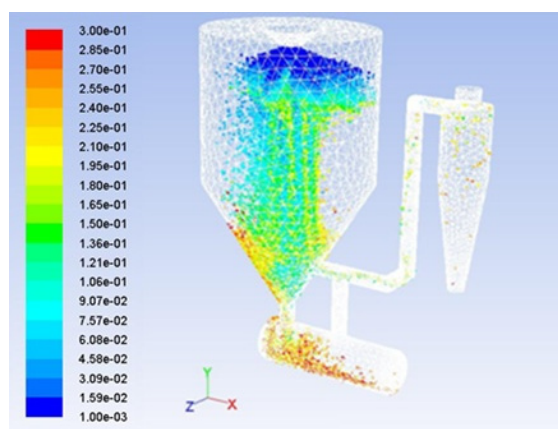


Fig. 9 Simulation for industrial setup of residence time (seconds) for spray drying process.

Conclusion

Stickiness arises during the process of spray drying, and this is important because it is a quality which can be utilized in controlling the potential enlargement of the particles being dried. This can lead to better quality powder and consequently a better quality of product. However, one problem which can occur due to stickiness is blockage in the cyclone; for this reason, it may be important in future to study stickiness in greater detail.

In this research, a simulation model was developed of the spray drying process based on the temperature and air flow profiles and the distribution of the residence time for skimmed milk powder within the spray dryer. The issue of stickiness was also examined.

Three-dimensional CFD simulation was performed for a co-current pilot plant spray dryer using a pressure nozzle for the purpose of spray drying skimmed milk powder. The data agreed with published experimental findings, suggesting that the CFD simulations could provide accurate predictions of the activity inside the spray dryer. The simulation identified that the air flow comprised a core flowing at high speed, with a slower zone of recirculation around the core. The droplets were dried in the region at the core, where smaller droplets typically evaporated due to the heat. The particle trajectories depended on the air flow patterns, which resulted in the residence time of the smaller particles exceeding that of the larger particles, with mean residence times for particles of sizes 40 μm , 70 μm and 100 μm of 1.6 s, 1.4 s and 1.2 s, respectively. The deposits resulting from stickiness typically were on the walls of the conical section, with the cylindrical section walls receiving far less material. When the droplet size was slightly increased, the result was an increase in the deposits on the walls due to stickiness.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

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