

Review

Mechanism of Particle Agglomeration for Single and Multi-Nozzle Atomization in Spray Drying: A Review

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Abstract: This paper reviews experimental works on the effects of single nozzle location and multi-nozzle atomization on the mechanism of particle agglomeration in spray drying. In addition to the naturally occurring primary agglomeration, forced and secondary agglomeration is observed as an effect of different nozzle positions or multiple-nozzle atomization in spray drying. Particle size diameters in the spray drying process for atomization from a single nozzle located at the top of the tower are larger than at the bottom of the tower because of the lower ambient air temperatures and longer residence time in the agglomeration zone. The trend of reduction in particle size is observed in all analyzed works when the nozzle is moved down towards the air inlet, due to droplets' exposure to higher air temperatures and shorter residence time in the drying chamber. Conditions of droplet-droplet, dry-dry or sticky-dry collisions leading to the development of coalescence, agglomeration and rebound zones for multiple-nozzle atomization are described and discussed. Typically, log normal PSD was found for single-nozzle spraying whereas for multi nozzle arrangement, bi-modal particle size distribution was found both for drying in lab and industrial scale.

Keywords: spray drying; agglomeration; multiple nozzles; single nozzle location



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1. Introduction

One of the common methods for producing dry loose material without prior grinding is spray drying. Spray drying involves atomization of a solution, slurry, or paste to form the droplets and contact with hot drying medium, usually air. In spray drying chambers, the feed is converted into micro-sized droplets via atomization, which facilitates a robust heat and mass transfer. Spray drying is a fast (10 sec-1min) convective drying process, in which hot air provides energy for evaporation of solvent in the form of liquid drops [1]. Over the years, spray drying has evolved as an industry-friendly drying technology with a wide range of applications in many sectors, including the food, pharmaceutical, and chemical industries [2].

Producing a powder with controlled particle size distribution (PSD) as well as particle shape and structure is still of paramount interest in the dairy, instant food, pharmaceutical, and detergent industries, and even in the production of medical and biological products [3,4].

The most common configuration of spray drying is co-current and counter-current process. In the co-current spray towers, both phases flow through the chamber in the same direction (downward), which is suitable for temperature-sensitive products. In the counter-current towers, the spray and the air are introduced at opposite ends of the dryer, with the atomizer positioned at the top and the air entering at the bottom [5]. Counter-current spray dryers offer high throughput, control of product bulk density, and an option for application of multilevel atomization [6].

Particles produced by spray drying can be smaller than 50 μm in diameter, leading to poor flowability and slower reconstitution or lump formation during rehydration, affecting

the quality of products. To overcome these problems, the agglomeration process can be applied to powders produced by the spray drying method. The required particle size can be achieved by particle agglomeration and control of particle size and properties, which is commonly implemented in the industry. There are various methods for particle agglomeration: direct agglomeration during drying [7–9], fluid-bed agglomeration [10], steam-jet agglomeration, and different pressure agglomeration processes [3].

Many theoretical attempts have been made to determine mechanism of the agglomeration process, such as by direct modelling [11–13], stochastic models [14–16], and particle populations balance models [17,18]; however, only a few agglomeration models have been validated due to difficulties in the industrial scale measurements and a lack of data on material properties (glass transition or stickiness), tower geometry, and flow hydrodynamics.

This paper reviews experimental works and experimentally validated theoretical models on the effect of nozzle system configuration on the mechanism of particle agglomeration in spray drying.

2. Agglomeration in Spray Drying

2.1. Study on Particle Agglomeration Mechanism in Spray Drying

Particle agglomeration is a complex and rapid process in spray drying affected by many factors, such as drying temperature, hydrodynamics of phases, material characteristics, and the configuration of the nozzles system [19].

Agglomeration can be described as the sticking of particulate solids, which is caused by short-range physical or chemical forces among the particles because of physical or chemical modifications of the surface of the solid [20]. Agglomeration can be defined as a process during which primary particles stick together so that bigger porous secondary particles (conglomerates) are formed, in which the original particles are still identifiable, Figure 1. In this way, the characteristics of a single particle are maintained, whereas the bulk powder properties are improved by the development of the larger agglomerates [19].

Agglomeration in the spray dryer chamber results from collisions between two or more particles [21]. With drying, stable solid bridges between particles are developed, leading to formation of a new bigger structure. Not every particle contact results in agglomeration; at least one of the colliding particles should have a sticky surface for adhesion [22]. To some extent, both primary and secondary agglomeration occur naturally in the spray chamber through random collisions of moving particles in the chamber [23].

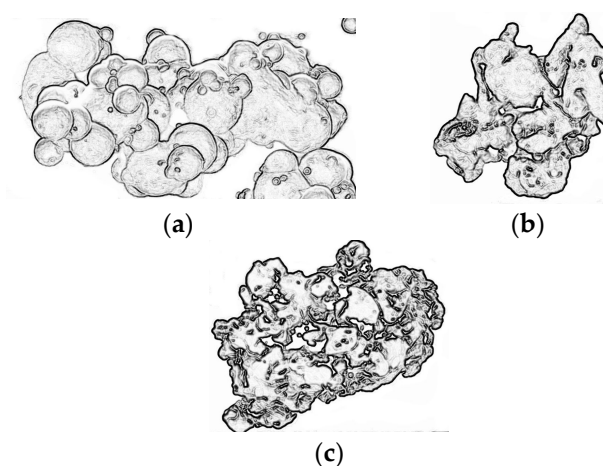


Figure 1. Examples of different agglomerates' structures adapted from Refs. [19,24,25].

When the surface reaches the sticky state, collisions with other particles (sticky or dry) could lead to agglomeration, depending on velocity, particle momentum, collision angle, and time of contact between particles [26,27].

Extensive analysis of the agglomeration mechanism in industrial spray drying towers was elaborated by Huntington [28]. The author distinguished the following mechanisms of agglomeration: droplet/droplet agglomeration within a spray cone, droplet/semi-dried particle, and particle/particle, taking place during particle flow as well as on the dryer wall. Huntington [28] claims that in counter-current industrial swirl dryers, agglomeration increases with increasing tower load, where the mass median diameter (MMD) grows by a factor of about three from droplet to the powder, whereas for nil-swirl, lightly loaded towers, MMD may double. Huntington, Ref. [28] concludes that to prevent production of excessive coarse product agglomeration process in spray drying, towers must be controlled.

Recently, Fröhlich [27], analyzed the effect of solid content in the feed solution on agglomerate formation. Drying of maltodextrin in pilot plant spray dryer showed that an increase in total solid content from 30 to 50% (w/w) resulted in an increased particle size from 44.7 to 64.6 μm . The authors attribute this effect to a changed particle viscosity, as increased solid content resulted in less coalescence of the agglomerates, concluding that the agglomeration in the atomization zone is controlled air hydrodynamics in the chamber.

Control of particle size and the agglomeration process can be achieved by proper configuration of the atomizing nozzles producing droplets [29]. In addition to the naturally occurring primary agglomeration, forced, secondary agglomeration is observed in many industrial applications as an effect of using different nozzle positions or multiple-nozzle atomization [9].

2.2. Particle Agglomeration and Product Quality

In the process of spray drying, particle agglomeration changes the structure and size of the particles (spherical or semi-spherical), thus affecting some properties of the final product, such as bulk density, porosity, solubility, and fluidity. Refs. [8,24], investigated agglomeration in spray drying towers for different numbers and locations of the nozzles to study and understand the mechanism of the particle agglomeration process. The agglomerates themselves evolve from grapelike structures at the finest fractions to complex shapes for large sizes (Figure 1). Through the agglomeration process, the primary particles become granule-shaped with improved dissolution characteristics, which quickly re-hydrate because of irregular structure and high porosity [3,22]. After agglomeration, the morphology of the particles is substantially changed, which improves the properties of the powder's functionalities (flow properties, dust generation, explosion risks, storage, mixing capacity, dispersion, solubility, and controlled release).

3. Effect of Nozzle System Configuration on Particle Agglomeration in Spray Drying

The rate of agglomeration and the size of the resulting agglomerates, in addition to the physicochemical properties of the atomized solution, are also influenced by the operating process parameters, the geometry of the tower, the method of phase contact (co-current, counter-current, or mixed) [30], and the configuration of the nozzle system. In this review, we focus on the analysis of the effect of nozzle arrangement for particle agglomeration in spray drying.

To determine of the influence of the nozzle system configuration on particle agglomeration more comprehensively, two aspects should be considered: one is the effect of a single nozzle at different locations in the drying chamber on particle agglomeration (nozzle height is generally relative to the hot air inlet), and the other is the effect of applying a multi-nozzle system (two or more nozzles atomizing simultaneously) on particle agglomeration.

3.1. The Effect of a Single Nozzle Position on Particle Agglomeration in Spray Drying

The position of the nozzle in a spray tower affects heat transfer and the velocity of the particles, which can influence particle agglomeration.

The first extensive experiments on agglomeration in spray drying to include in situ PDA laser measurements of particle size distribution in a tower were carried out by

Zbicinski and Piatkowski [31], and Piatkowski [32]. The agglomeration process was studied in the counter-current 8 m high and 0.5 m diameter spray drying tower (Figure 2).

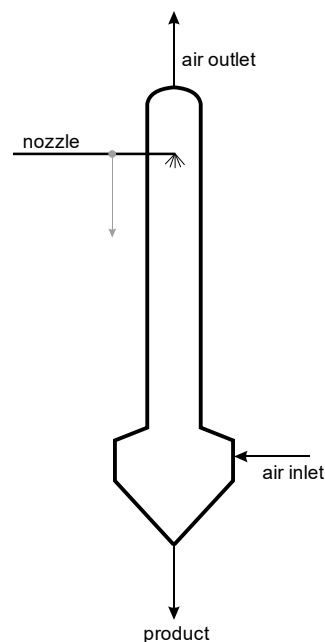


Figure 2. Counter-current spray drying tower.

The position of the nozzle in the tower was changed against the distance of the air inlet, which allowed analyses of the effect of nozzle location on drying and agglomeration. The nozzle was installed in three different positions from the air inlet: 2.4 m, 4.7 m, and 6.7 m.

Figure 3 shows a comparison of average particle diameters along the drying tower for three different nozzle locations and different process parameters; the final average diameter of agglomerates changed from 150 to 450 μm . The most intensive agglomeration and the highest average particle growth was observed when the nozzle was installed at 4.7 m and 6.7 m from the air inlet.

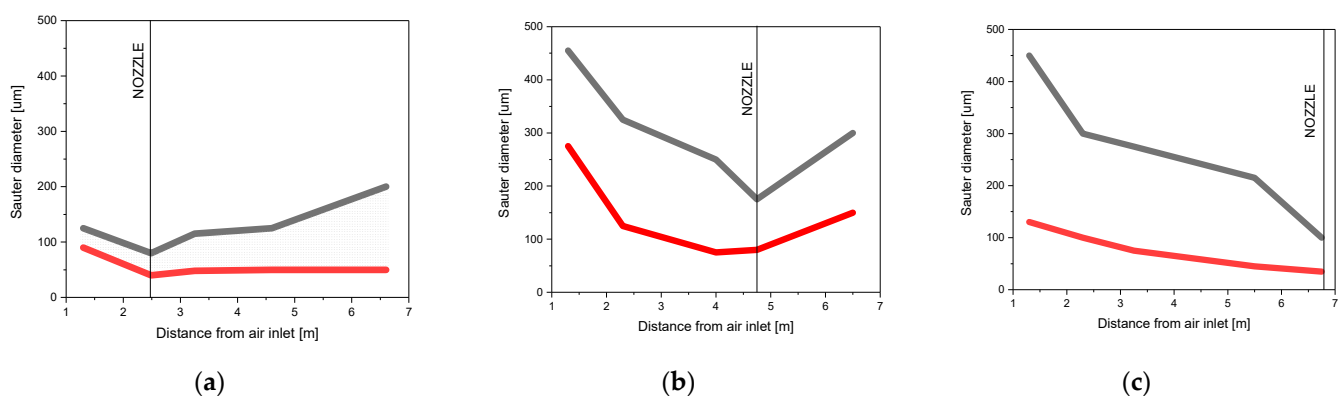


Figure 3. Area of changes of an average particle diameter along the drying tower for different nozzle positions (a–c), slurry and airflow rate, swirl flow, atomization ratio, and air temperatures.

Results of the experiments proved that the position of the nozzle in relation to the hot air inlet had a significant influence on the agglomeration process. Phenomena decisive for the course of agglomeration take place in the atomization zone, i.e., the area from the nozzle to about 1.5 m below the nozzle. By changing the location of the nozzle, the temperature and air velocity profiles—which are in direct contact with the sprayed particles—are changed.

For the nozzle installed at 2.4 m from the air inlet, the final particle diameters were relatively small because the high air temperature in the atomization zone hindered agglomeration, and the final particle diameters for these conditions in most cases did not exceed 150 μm . The poor agglomeration of the particles was the result of the rapid evaporation of moisture and the establishment of a low adhesive particle structure, so that contact between the particles did not lead to the formation of the agglomerates.

The displacement of the nozzle from 2.4 m to 4.7 m from the air inlet caused the material to be sprayed into the air with different velocity profiles and, most significant of all, to lower air temperature by about 20 $^{\circ}\text{C}$. Under these conditions, the agglomeration process was more effective, and the maximum particle diameters for several drying conditions reached approx. 450 μm and were even 10 times larger than the average initial droplet diameters released from the atomizer.

Another change of the nozzle position (to the level of 6.7 m from the air inlet) did not significantly change the size of agglomerates; an average diameter size obtained under these conditions was up to 400 μm .

PDA analysis showed negative value of the particle velocity in the drying chamber, which confirmed the existence of particle agglomeration recycling zones in counter-current spray drying [32].

Similar research was carried out by Francia [8,24], who investigated particle growth in a pilot plant counter-current swirl dryer for detergents, operating with one nozzle at three locations (8.2D, 5.9D, 3.5D). Figure 4 shows a comparison of the product mass-based particle size distribution for different nozzle locations. In each case for single nozzles, mono-modal size distributions were obtained. When the spray nozzle was located at the top position (a distance of 8.2D from the air inlet), the size of the product was significantly higher (between 600 to 850 μm), which implied intensive growth into the large fractions. For the nozzle located at distance of 5.9D from the air inlet, the growth of the size of the product was reduced. The trend of reduction of the particle size continued when the nozzle was moved further down to the lowest distance from the air inlet (3.5D), because of droplets' exposure to higher air temperatures. In a high-temperature environment, the outer crust of droplets was produced earlier, the surface was less prone to stick and with lower residence time, and agglomeration was suppressed. When spraying from higher nozzles locations, due to longer residence time and lower ambient air temperatures, the particle aggregation increases.

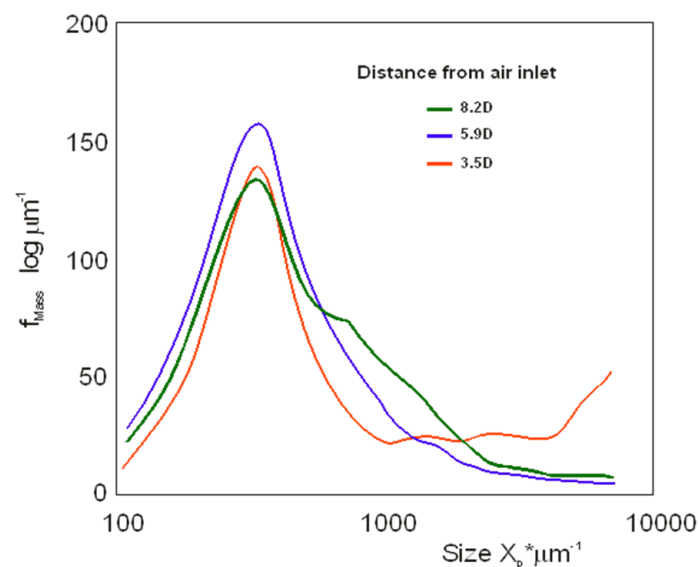


Figure 4. Comparison of the product mass based size distribution obtained under different nozzle locations Ref. [7].

However, when the nozzle was situated at the lowest distance from the air inlet (3.5D), the proportion of particles in the powder with size $> 850 \mu\text{m}$ was larger than at higher distances from the air inlet ($>35\%$ of the production, versus 24% and 14%, respectively), which means that the mechanism of particle growth might be different to inter-particle contacts. The authors of [8] suggest that interaction of particles with the wall deposits may lower disruptive stresses of the agglomerates and promote re-entrainment of large granules to the chamber.

Recently, Piatkowski et al. [33] experimentally studied particle size distribution, particle velocities, and air flow pattern in a counter-current pilot plant drying tower (8 m in height and 0.5 m in diameter) above and below the nozzles located at the top and close to the air inlet. A schematic of the pilot plant tower and location of the nozzles and levels of PDA measurements are shown in Figure 5.

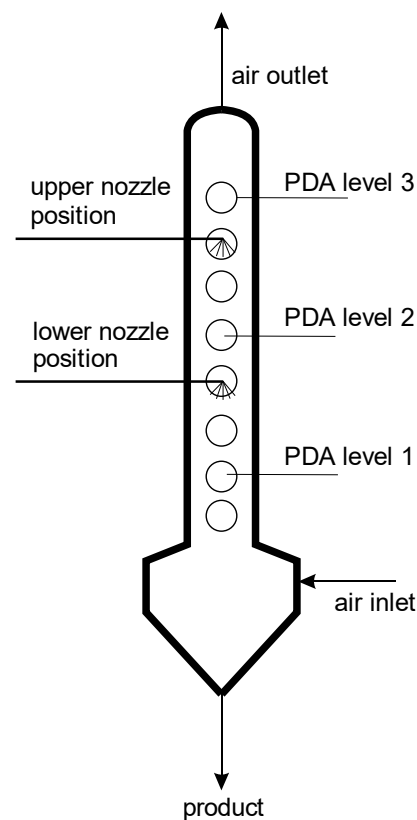


Figure 5. Schematic of pilot plant tower.

PDA measurements carried out below and above the nozzle trace changes in particle size distribution and particle velocities at the axis and near the wall (0.22 m from the axis). Downward air flow in the axis area and upward flow near the wall of the tower cause collisions and promote agglomeration of the particles. Figure 6a,b shows the particle size distribution of the product for the nozzles at the top and the bottom positions in the tower. Figure 6a shows that PSD above the nozzle is smaller, both at the axis ($D_{32} = 25.4 \mu\text{m}$) and at the wall ($D_{32} = 78 \mu\text{m}$), in comparison with particles measured below the nozzle ($D_{32} = 69.5 \mu\text{m}$) and at the wall ($D_{32} = 96.6 \mu\text{m}$), which is a result of intensive agglomeration in the recirculation zones below the nozzle, whereas smaller and lighter particles were entrained with upward airflow to the cyclones. The presence of a large number of smaller particles at the axis results from airflow hydrodynamics, as swirl flow in the chamber moves bigger particles to the wall of the tower.

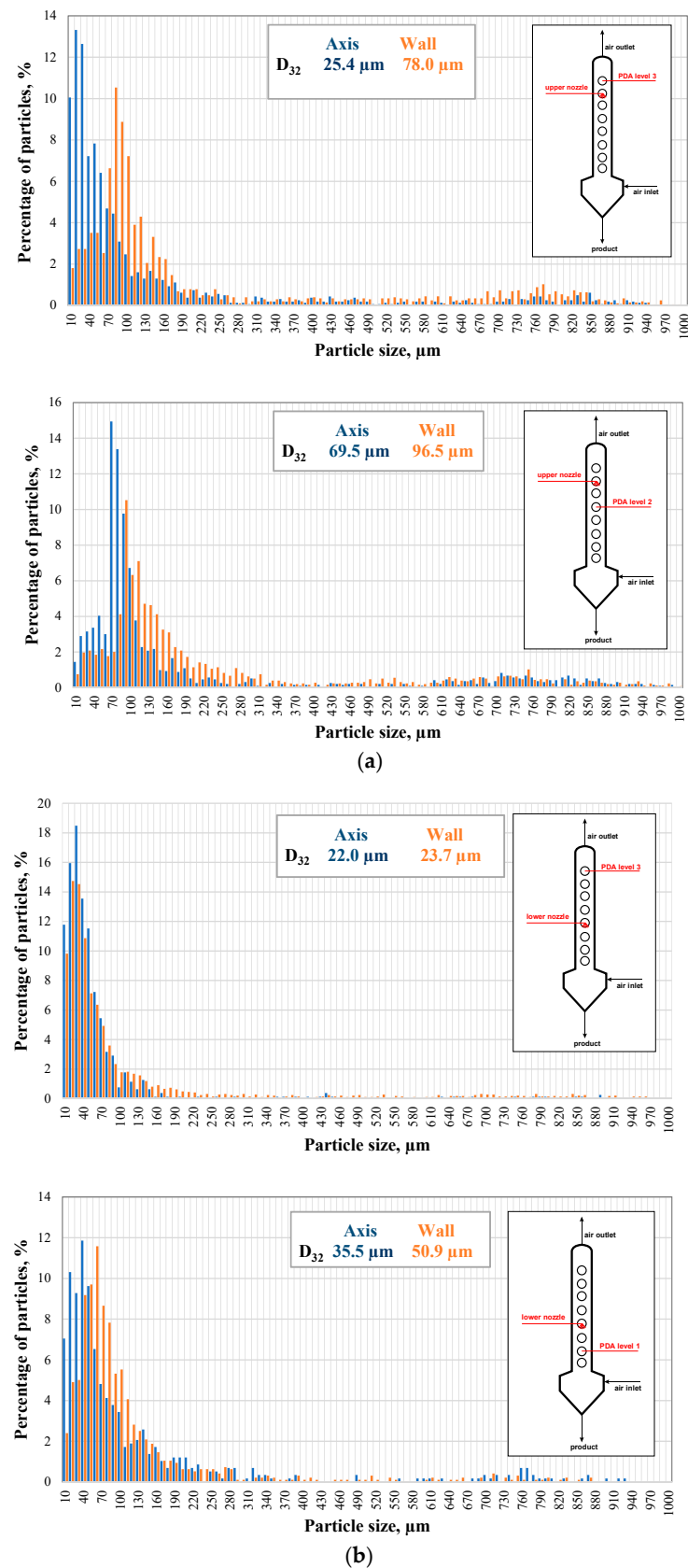


Figure 6. ((a) Nozzle at the top (b) Nozzle at the bottom) PSD at the axis and at the wall above and below the nozzle (adapted from Ref. [33]).

A similar PSD was observed when the nozzle was situated lower in the dryer, near the air inlet, Figure 6b. The particles above the nozzle are smaller both at the axis ($D_{32} = 22.0 \mu\text{m}$) and at the wall ($D_{32} = 23.7 \mu\text{m}$) in comparison with particles found below the nozzle ($D_{32} = 35.5 \mu\text{m}$) and at the wall ($D_{32} = 50.9 \mu\text{m}$).

Comparing PSD of the particles for the nozzle located at the top and at the bottom of the tower, we observe smaller particle diameters at the bottom and bigger for the top nozzle positions. Reduction in particle size when moving the nozzle down to the air inlet is a result of droplets' exposure to higher air temperatures, which hampers the agglomeration process [8,24].

The authors also showed that for a nozzle situated at the top of the dryer, where the air temperature in the atomization zone is lower, intensive air circulation promotes agglomeration of the particles in the form of large uniform structures (Figure 7a). For the lower position of the nozzle (closer to air inlet), the high air temperature in the atomization zone hinders agglomeration in the form of spheres and develops complex 3D structures consisting of many smaller particles (Figure 7b).

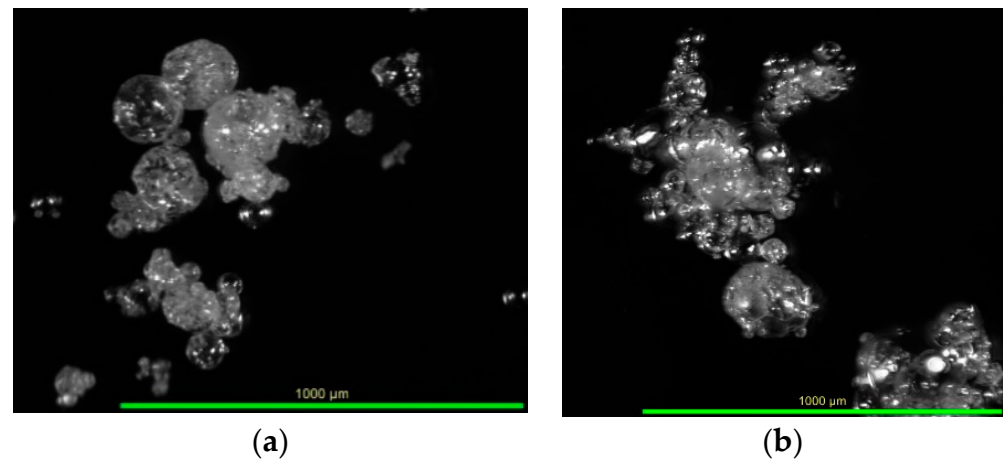


Figure 7. Product photos from the stereoscopic microscope for the nozzle at the top position (a) and bottom position (b) (adapted from Ref. [33]).

Distance from the nozzle to the air inlet has a decisive effect on the agglomeration of particles in the counter-current system; nozzle location and appropriate selection of drying process parameters enable control of particle structure in the spray drying process.

3.2. Particle Agglomeration in Multiple-Nozzle System Atomization

The concept of multiple-nozzle spraying means using single nozzles on different levels or several nozzles on each level in the drying chamber [34]. Only a few researchers have carried out experiments on agglomeration for a multiple-nozzle system; mostly mathematical models are used to simulate particle agglomeration without experimental verification [17,35]

Francia et al. [25] studied agglomeration in a counter-current dryer between multiple spraying levels. In contrary to the application of single nozzles, a multi-nozzle arrangement generates bi-modal particle size distributions (PSD). Figure 8 presents product size distributions between 300–425 μm , with a typical log-normal shape for single-nozzle operation. The use of two sprays (3.5D and 8.2D from the air inlet) generates a bi-modal-shaped PSD, with a second mode between 850–1180 μm .

The authors estimated that inter-nozzle interactions account for the production of >6–11% of agglomerates > 600 μm .

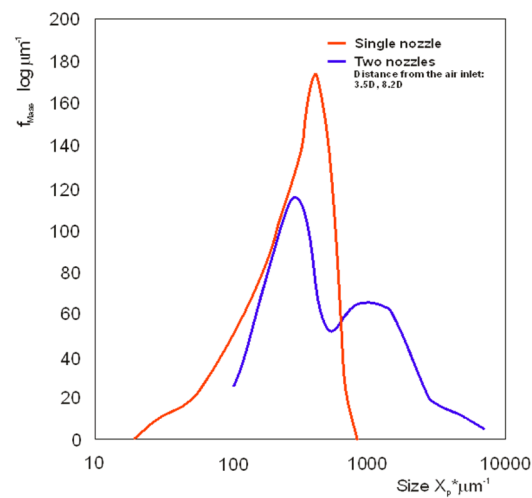


Figure 8. Product size distribution for single- and multi-nozzle operation (3.5D and 8.2D from air inlet).

Francia et al. [8] also examined the effect of air flow conditions (air temperature and velocity) on agglomeration in an industrial swirl spray tower for the drying of detergents, for a single- and double-nozzle arrangement. The authors confirmed that the particle size of powder responds to changes in the air flow in the drying chamber. High air velocity in the chamber makes droplets and particles swirl faster, which moves particles to the wall where the agglomerates are constantly forming and breaking. This mechanism occurs independently of dryer throughput and nozzle location, both for single and multiple nozzles, and inhibits the development of coarse aggregates $> 850 \mu\text{m}$.

Wawrzyniak et al. [36] applied PDA measurements to determine the effect of spray direction of two nozzles on the final properties of the products in a pilot plant drying tower (Figure 5). The upper nozzle was installed 5.05 m above the air inlet and sprayed downwards, whereas the lower nozzle at 2.8 m above the air inlet sprayed in two directions: downwards (Test A) and upwards (Test B) (Figure 9). The results confirmed bi-modal PSD for both configurations of the nozzles spraying in downward and upward direction (see Figure 8). The drying zone under the lower nozzle and agglomeration zone between the nozzles were detected when the two nozzles sprayed downwards (Test A). Below the lower nozzle, reduced agglomeration was determined, as the slurry was sprayed into the hot air, which made the particles less prone to stick, also due to short residence time. Only smaller and lighter particles were flowing upward to the agglomeration zone between the nozzles.

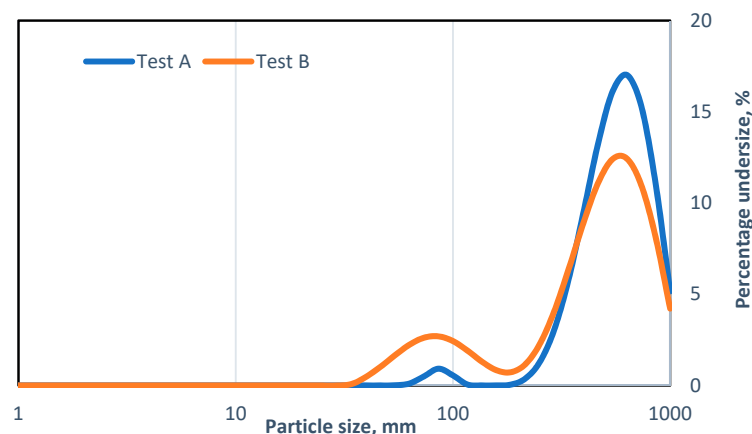


Figure 9. Product particle size distribution for two nozzles spraying downwards (Test A) and for lower nozzle spraying upwards (Test B) (adapted from Ref. [36]).

When the upper nozzle sprayed downward and lower nozzle sprayed upward (Test B), intensive agglomeration between the nozzles was observed. The particles sprayed by the lower nozzle quickly fall into a stream of moist particles from the upper nozzle.

Average powder PSD for Test A and B are similar, $D_{50} = 542 \mu\text{m}$ and $460 \mu\text{m}$, respectively; however, PSD for Test B has a more pronounced two-peak character (Figure 9).

Jubaer et al. [9] studied forced agglomeration to predict coalescence, agglomeration, and elastic rebound zones in a lab-scale counter-current spray dryer with two-nozzle atomization. Figure 10 shows schematic of a lab spray dryer with nozzle locations; the primary (main) nozzle is installed at the top and the secondary nozzles (positions 1 to 3) are inclined perpendicularly or at an angle of 45° to the dryer wall. The arrangements of the of the secondary nozzles simulates fine returns, which is a typical method in the industry for controlling and promoting the agglomeration process [23].

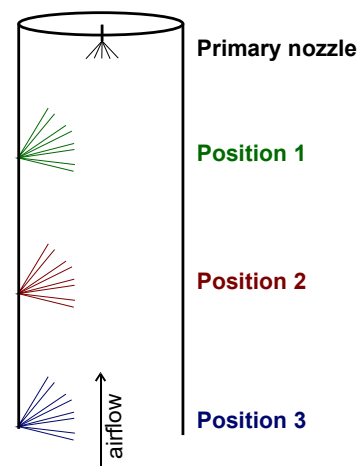


Figure 10. Schematic of lab spray dryer with nozzle locations; primary nozzle at the top and the secondary nozzles (positions 1 to 3, Ref. [9]).

During drying experiments, skim milk with 10% initial solid content was sprayed from primary (top nozzle) and one of the secondary nozzles. To obtain profound picture of agglomeration mechanism, CFD model was developed and validated on the basis of the experimental data of particle size distribution and SEM analyses of the powder morphology.

The trials showed significant differences in particle size and morphology for spray drying with different secondary nozzles locations.

Results of the work are summarized in Figure 11 which shows interaction of sprays developing droplet, sticky and dry zones in the drying chamber for different secondary nozzle configurations (Position 1, 2, 3, [9]). For the position 1 of secondary nozzle droplet-droplet collisions dominates due to short distance between secondary and primary nozzles. In the position 2 sticky particles from both sprays could collide forming sticky-sticky or sticky-dry collision zone (the most effective for agglomeration). For position 3 of the secondary nozzle, where most of the particles are dry; dry-dry or sticky-dry collisions zone occurs. Similar particles behavior was observed for the case when the secondary nozzles were positioned at an upward angle.

The Authors claim that the position 2 of the secondary nozzle located upward produce the most intensive forced agglomeration. Asymmetry introduced by the single secondary injection might affect air temperature and velocity in the chamber and increase the wall deposition.

Cumulative distribution of particle size for experiments with different nozzle configurations are shown in Figure 12. Analysis of Figure 12 confirms size enlargement of the particles for each trail with secondary nozzle atomization; however, the extent of the enlargement is different for different secondary nozzle locations. The most significant size enlargement was obtained when the secondary nozzle was located at Position 2 (both for

perpendicular and upward spraying angle) due to the highest probability of sticky–sticky and sticky–dry particle contacts. The particle size distribution at Position 1 is slightly smaller than that of Position 2, as agglomeration there develops only by coalescence. The smallest diameter enlargement was observed for a secondary nozzle situated at Position 3 due to droplets' exposure to higher air temperatures, which is in line with conclusions made by Francia [24]. The most intensive agglomeration was found for nozzle spraying upward at Position 2.

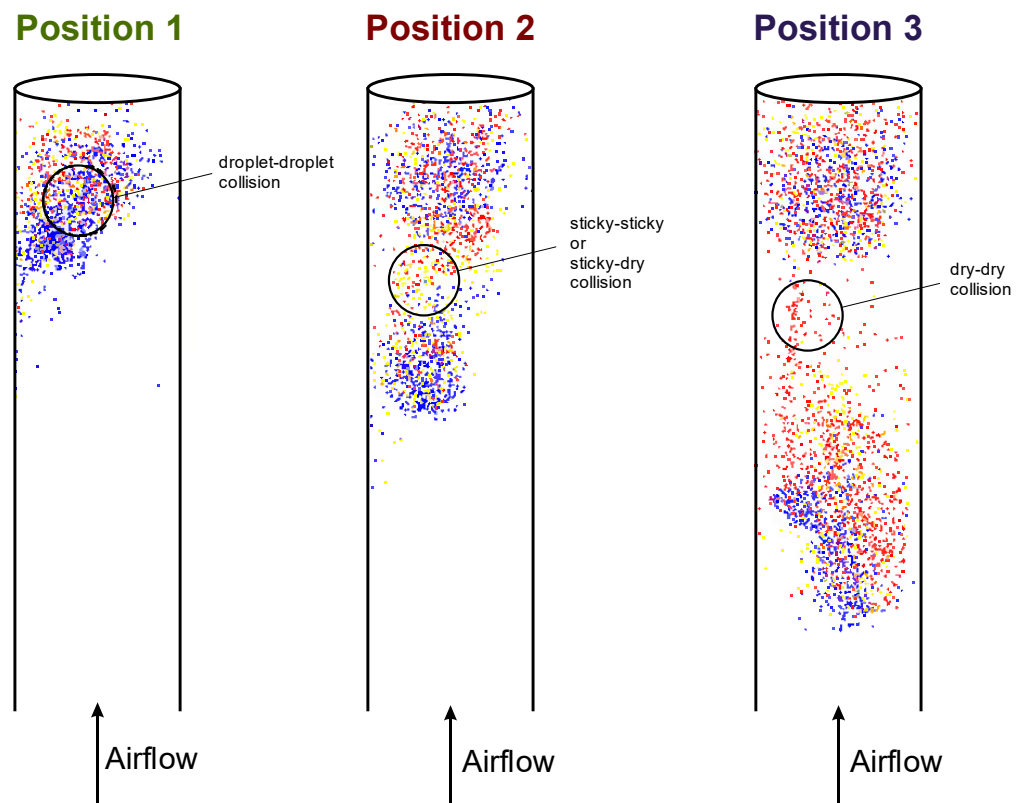


Figure 11. Location of droplet, sticky, and dry collision zones for different nozzle configurations (Position 1, 2, 3, Ref. [9]).

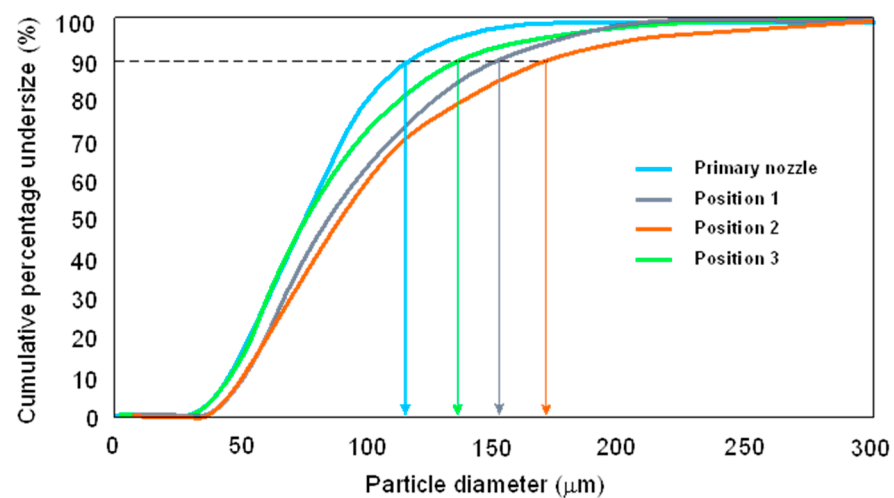


Figure 12. Comparison of particle size distributions of the powder samples collected from the experimental trials for all tested nozzle positions Ref. [9].

Wawrzyniak et al. [37,38] analyzed the agglomeration process in a 37 m high and 6 m diameter nil-swirl industrial spray drying tower for detergent production. The slurry was sprayed by 12 nozzles an angle of 65° located on two levels of 18 m and at 10 m from the hot air inlets (Figure 13).

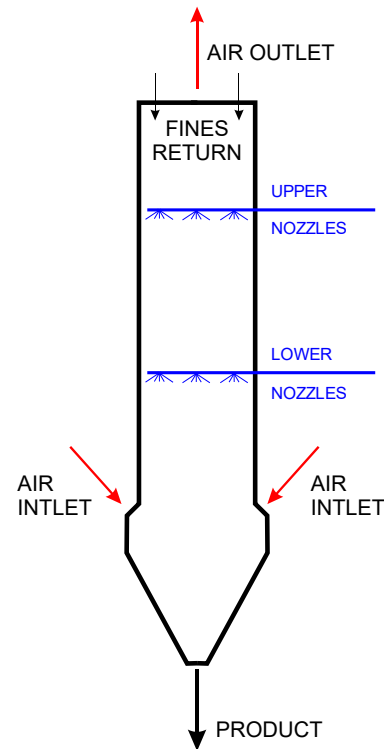


Figure 13. Schematic of industrial spray dryer for detergents with nozzle locations.

The lack of swirl due to the geometry of the tower and construction of the air inlet ring resulted in high instability of air flow in the tower. A robust agglomeration process was observed in the tower, as the initial average particle size increased from $285\ \mu\text{m}$ to the final $770\ \mu\text{m}$ in the product. The initial velocity of particles was $50\ \text{m/s}$. Cumulative initial and final and percentage undersizing PSD in the industrial tower are presented in Figure 14.

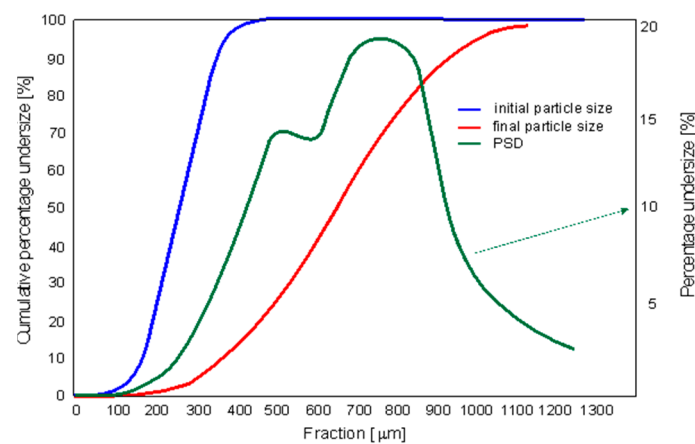


Figure 14. Cumulative initial and final and percentage undersized PSD in the industrial tower.

Experimentally determined percentage undersized PSD shows a bi-modal distribution as in [25,36].

To determine mechanism of agglomeration in the nil-swirl industrial dryer, CFD of particle flow was developed. The model was verified indirectly based on temperature and velocity measurements in the industrial tower using “negative heat source concept” described in [38]. By analyzing the residence time of particles in the drying tower and the diameter growth, the zones of particles agglomeration were determined. Residence time of particles in the dryer was found to be in range from 20 to 60 sec. Average agglomeration time was estimated as 20 sec. Two particle recirculation zones, above the upper and below the lower nozzles level in the dryer were detected (Figure 15). Small particles injected at the upper nozzles level followed air path lines, whereas bigger particles fell with the progress of the agglomeration and leave the dryer.

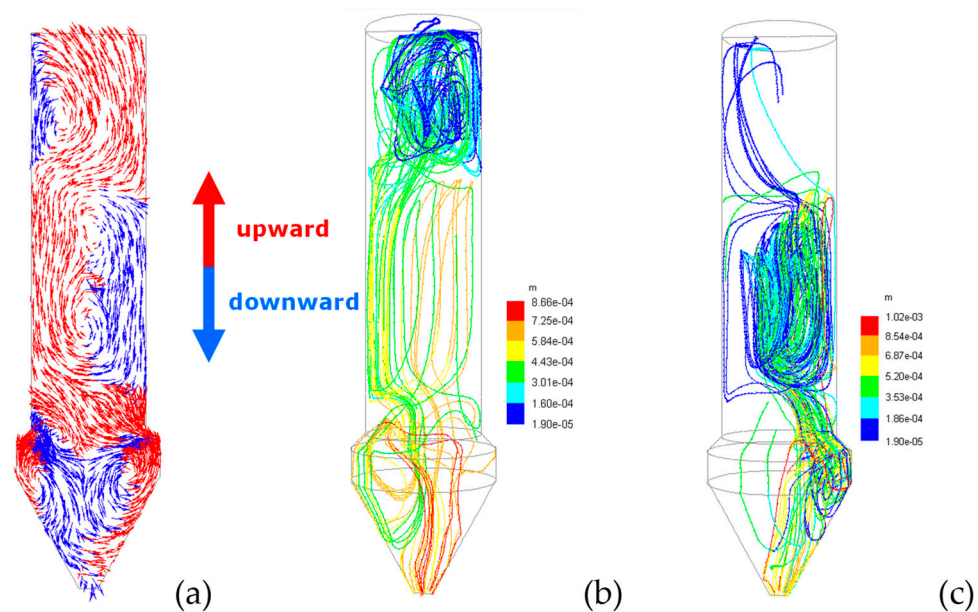


Figure 15. Comparison of drying air flow (a) and particle trajectories for upper (b) and lower (c) nozzles level, Ref. [38].

Diameters of larger fractions increase due to the collisions with wet particles produced by the nozzles from the upper level, but also due to the agglomeration with particles entrained with the air from the lower level. Finally, particles produced at the upper nozzle level are larger than the particles with similar initial diameters released from the lower level because of the longer residence time in the agglomeration zone.

Based on experiments in an industrial tower ([38]), Jaskulski et al. [39] confirmed the mechanism of agglomeration in the industrial tower (Figure 12) using a CFD agglomeration model accounting for collisions of droplets and particles and coupling of agglomeration with heat, mass, and momentum transfer for the industrial tower. Fine and dry fractions were entrained above the atomizing nozzle but did not agglomerate, as the lower moisture content hampered the formation of liquid bridges between the particles during collisions.

Similar conclusions regarding the mechanism of agglomeration were presented by Nijdam et al. [17], who researched the agglomeration process for one and two nozzles pointing toward each other and spraying water. The authors showed that the inertia of a droplet plays an important role in droplet movement in the spray drying chamber. Larger droplets tend to concentrate on the outer part of the spray, maintaining radial momentum further downstream from the nozzle, whereas smaller droplets follow the air flow more closely at the core of the spray. Both turbulent collisions and difference in droplet relative velocity can promote agglomeration. The authors confirmed that besides primary agglomeration, forced and secondary agglomeration occurs as an effect of different nozzle positions.

4. Conclusions

Intensive agglomeration is observed in industrial spray drying towers, which results in a significant increase in the particle diameter of the product. Powder containing small particles, commonly produced in spray drying, is characterized by poor flowability, slower reconstitution, or lump formation during rehydration. Agglomeration changes the morphology of the particles, improving the powder's functionalities such as particle shape, bulk density, porosity, solubility, and fluidity. Most works in the literature examine agglomeration in spray drying and the hydrodynamics of phase contact (co-current, counter-current, or mixed) and the effect of physicochemical properties of the atomized solution, the spray drying process parameters, and method of feed atomization in controlling the rate of agglomeration and size of the agglomerates. The literature review carried out in this paper reveals a strong effect of nozzle location and multi-nozzle atomization on the mechanism of particle agglomeration in spray drying.

The coarse agglomeration mode is mainly generated by spraying from the top of drying towers because of the longer residence time and lower ambient air temperature in the agglomeration zone. Agglomeration growths are inhibited when the nozzles are located near the bottom the tower due to contacting the high inlet air temperature and short residence time, which hampers the formation of liquid bridges between the particles.

For multiple-nozzle atomization, droplet–droplet, dry–dry or sticky–dry particle collisions form coalescence, agglomeration, and rebound zones. Log normal PSD, characteristic for single-nozzle atomization, turns into bi-modal for multi-nozzle arrangements.

Literature analysis proves that atomization from multiple nozzles promotes agglomeration by increasing collision rate, collision frequency and efficiency, increasing the probability of particle growth with the aid of air flow recirculation in the chamber.

In future work, the research of the effect of spray direction of the nozzles on the mechanism of particle agglomeration, final properties of the products and reduction of the wall deposition in co- and counter-current spray drying will be carried out.

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