Atomization for Spray Drying: Unanswered Questions and Industrial Needs

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Abstract

This paper introduces the atomization community to the unique and unmet challenges of spray drying, with an emphasis on industrial needs to understand atomization of complex fluids. The fluids are typically concentrated, viscous, non-Newtonian, sometimes contain suspended solids, and typically run at flow rates exceeding a ton per hour; most atomization literature treats fuels and other low-viscosity liquids at substantially lower rates. Some specific needs are presented as a challenge to the academic community.

Introduction to Spray Drying

Spray drying is a major unit operation that produces thousands of tons a year of literally hundreds of products. These range from instant foods, such as coffee or milk, to heavy-duty chemicals, such as catalyst particles and dry laundry detergent [1].

The objective of the spray-drying process is to convert a liquid or slurry feed into a dry powder. In this continuous process, liquid feed is pumped to an atomizer and converted to droplets. A hot gas phase (usually air) contacts the spray and dries the individual droplets. The dry particles are collected in the bottom of the dryer or by cyclones or baghouses.

The atomizer type and dryer geometry are closely related. Figure 1 shows a few typical spray drying systems. A spinning wheel atomizer, typically used in co-current dryers with abrasive feeds, has a large diameter to minimize deposition on the wall. Spray dryers with nozzles, either pressure nozzles or pneumatic nozzles usually have a smaller diameter and have co-current air flow. Our dry laundry towers are counter current and contain numerous pressure-swirl nozzles. The selection of dryer type depends on the product attributes sought. However, product demands change more frequently than new dryers are purchased, so it is up to the engineers to figure out how to create the right particles with existing equipment.

Atomization is the first critical transformation occurring within the process. This paper highlights the roles that atomization plays in the process, what the industry needs to know, and why this problem has not been solved in the last 135 years since the process was invented [2].

Important Particle-Formation Mechanisms in Spray Drying

A liquid feed entering a spray dryer undergoes a series of complex processes to become a powder. These are illustrated in Figure 2. To begin with, the feed needs to be atomized into droplets. The feed material is normally as concentrated as possible to maximize throughput for a given capital investment. So the feed is typically viscous and non-Newtonian and often contains solid particles. These droplets immediately begin to dry upon contact with the hot air, sometimes before atomization is complete. All these factors affect the atomization process and lead to particle size distributions which are difficult to determine and, due to the presence of solids, can have size dependent compositions [3]!

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The transformations occurring within a single droplet are equally complex. The particle size distribution is generally not the same as the original droplet size distribution. One cannot simply measure particle size exiting the dryer and deduce the droplet-size distribution [4]. A drying droplet may shrink during drying due to loss of water, or it may expand or "puff" if it reaches the boiling temperature. Furthermore, the air in the dryer is turbulent and contains substantial temperature gradients, so each droplet follows a unique trajectory and has a unique experience. The partially-dry droplets can collide with each other in mid-air to form agglomerates or make-up on the dryer walls. Thus the evolution of the particle morphology, and granule properties, is clearly a complex stochastic process.

The Grand Challenge: Controlling Quality Attributes

"Drying", by itself, is easy to accomplish. The magic is in creating particles that have desirable attributes using a robust, controllable, and economical process. The focus of spray-drying research is to understand, via experimentation and modeling, how to connect the process design and operation to the powder attributes.

Table 1 shows key quality attributes for spray-dried laundry detergent [5], a product most familiar to the authors. Many of these apply to other spray-dried products as well.

Attribute	Relevance to Consumer	Relevance to Process
Particle Size	Particles that are too small create a dust plume during use Particles that are too big won't dissolve.	Particles that are too small can't be collected and handled effectively. Process fines need to be filtered from exhaust air. Particles that are too large are likely to stick to dryer walls and need to be recycled. Process overs are frequently ground and recycled.
Bulk Density	Consumer uses a scoop to deliver the product; density control essential for proper dosing.	Bulk density needs to be correct for accurate filling of packages.
Color	Consumers desire a clean, bright product	High temperatures lead to high throughput, but charring is unacceptable and leads to scrap.
Morphology	Consumers desire a free-flowing product that is not cakey.	Particle morphology affects powder flow and filling and particle attrition.
Dissolution Rate	The product needs to fully dissolve to be effective and not leave a residue.	Insoluble material accumulating within a process can lead to lower process reliability

Table 1. Consumer- and process-relevant powder attributes from a spray-drying process.

Researchers have worked for many years on various elements of this problem. These include modeling of the periodically transient air turbulence within spray dryers [6], drying / "puffing" of single droplets [7], agglomeration [8], and wall deposition [9].

Recently, there have been some notable efforts to combine these mechanisms into a grand computational model [10]. Invariably, these involve simplification of the physics to enable reasonable computation times. The atomization process is not modeled along with these other processes. Instead, the atomization process has been decoupled from the other processes and used as a boundary condition for the rest of the model.

Unfortunately, most of the published spray drying research is on small-scale dryers with dilute feeds. Smaller dryers make smaller particles. Besides the very basic mass and energy balances, most of the processes, including atomization, are not scaleable in a reliable way. Therefore, most spray-drying innovation today requires expensive testing on a large scale by process developers who rely on experience. This is effective to make a process work, but the resulting process and product are probably far from optimal.

Atomization Research Needs for Spray Drying

Most of the atomization research is conducted on low-viscosity liquids, *e.g.* fuels. These efforts teach spray drying researchers the fundamentals of atomization; they are useful from an educational perspective, but cannot be used directly. The needs can be divided into experiments, models, and atomizer design.

Experiments

Historically, correlations for atomizer performance have been semi-empirical fits to experimental data sets. More experimental data are necessary for direct use and for validation of theory. Specifically:

1. Experimental data from large nozzles. The vast majority of the experimental studies to date are on small nozzles with low-viscosity fluids, such as water or fuels. One notable paper on atomization of water from large-scale pressure nozzles states, “Drop size correlations in the literature based on small nozzles cannot generally be extrapolated to predict sizes from large nozzles” [11]. We have done some work on atomization of high flows of viscous liquids in our lab as well [4]. The density of these sprays presents challenges both to making the actual measurements and in the positional dependence of the particle size distribution. The high density makes droplet collision and coalescence more likely and therefore increases the importance of this mechanism within the spray cone.

2. Scaled-down test methods and analysis. Large-scale experimentation is expensive and difficult, as shown in Figure 3. This is particularly difficult in the case of slurries because small nozzles will clog with the solid particles. We need creative approaches to be able to get these data easier.

3. Rheology measurements relevant for atomization. There are many experimental techniques one can use to measure the rheology of complex, non-Newtonian fluids. For example, one can use a cup-and-bob rheometer for shear rates up to about 1000 s^{-1}, a capillary rheometer for shear rates to 100,000 s^{-1}, and special experimental equipment can be used to characterize “extensional viscosity”, cited as important for atomization [12,13]. In atomization of slurries, it is sometimes the liquid phase rheology which is important rather than the overall slurry rheology as this can be correlated to droplet size [3]. We need a road map to know what method to use to better understand our data.

4. *In-situ* measurements within dryers. Measurement of atomization and particle formation occurring within operating spray dryers is quite challenging due to the large dimensions of a dryer, the small length scale of the droplets, and the heat. The most comprehensive work on this subject is by the group in Lodz, Poland [14]; they have constructed a pilot-scale dryer where they are able to measure droplet/particle sizes as a function of position, air temperature, and other important values. Published data on large scale dryers are virtually non-existent, though the authors are aware of some attempts as well as their limited efforts. The industry needs methods and devices to get inside production scale dryers for R&D and process control.

Models

A variety of modeling techniques can be used for spray dryers depending on the requirements of the exercise. These are summarized well by Oakley [17]. The initial atomization parameters are a requirement for both full CFD models and for simplified dynamic models as both require a value for the drying rate which is, of course, dependent on drop size. These models are the minimum necessary frameworks which can be used to predict the quality attributes discussed above. Often estimates of drop size distributions are used in these models; hence if the challenges above can be overcome, then the data can be used for developing empirical models. These experiments therefore need to be set-up with this in mind and with a view to the learnings being as universally applicable as possible. However it should be said the latest CFD models [10] require very detailed information about the spray, *e.g.* particle size to velocity correlations, concentration fluctuations, etc. in order to predict phenomena such as agglomeration. These are difficult to measure and an area where perhaps first principle modeling can help.

First principle predictions of drop size distribution are not possible even for simple Newtonian fluids, though they have been used to gain some useful insights into the dense primary breakup region [15]. They offer similar benefits to the even more complex situation present in spray dryers where there are: 1. very high flow rates leading to very high spray densities, 2. complex rheology, 3. suspended particles and 4. evaporation and hence rapidly changing material properties. Some of these factors have been separately incorporated into models and researchers are beginning to look at incorporating a third phase into liquid break-up models [16]. The incorporation and solution of a model capturing all these interacting mechanisms sets a goal for which the spray drying and atomization community should aspire!

Atomizer Design

Since most of the atomization research and applications are for low-flow sprays using low-viscosity liquids, there is probably considerable room for innovation to enable atomization of highly viscous materials. In many atomization applications, like combustion, smaller drops are preferred; in spray drying, the foremost desire is a narrow particle size distribution. Industrial spray-dried products typically need to be screened to remove oversize particles and dust in exit air streams need to be collected. “Mono-dispersed” droplets can be produced in labs using exotic, low-flow techniques, such as ultrasound, however, these are not yet viable at ton per hour scales.

Capacity and energy usage are also chief concerns for spray-drying process developers. These considerations favor the use of concentrated feeds. For example, a 30% solids feed will use approximately 1470 kcal/kg of dried solid whereas a 70% solids feed will use only about 280 kcal/kg (3% product moisture content) [17]. Furthermore, the throughput of a given spray dryer is given by its evaporative capacity. Using the example above, a given dryer can produce more than five times the powder by concentrating the feed from 30 to 70%. Quite often, the limit of concentration is dictated by atomization. The industry needs new and better ways to atomize highly viscous and concentrated feeds. We need to be able to atomize the “impossible” to a tight, controllable droplet-size distribution.

Conclusion

Atomization of concentrated feedstocks for spray drying is ripe with difficult and unsolved problems that can be excellent research opportunities for academia. The challenges range from experimental techniques, to models, to novel atomizer designs. Isolating this important transformation and learning how to study and optimize it will contribute to faster development of more efficient, and environment-friendly processes that produce better materials.

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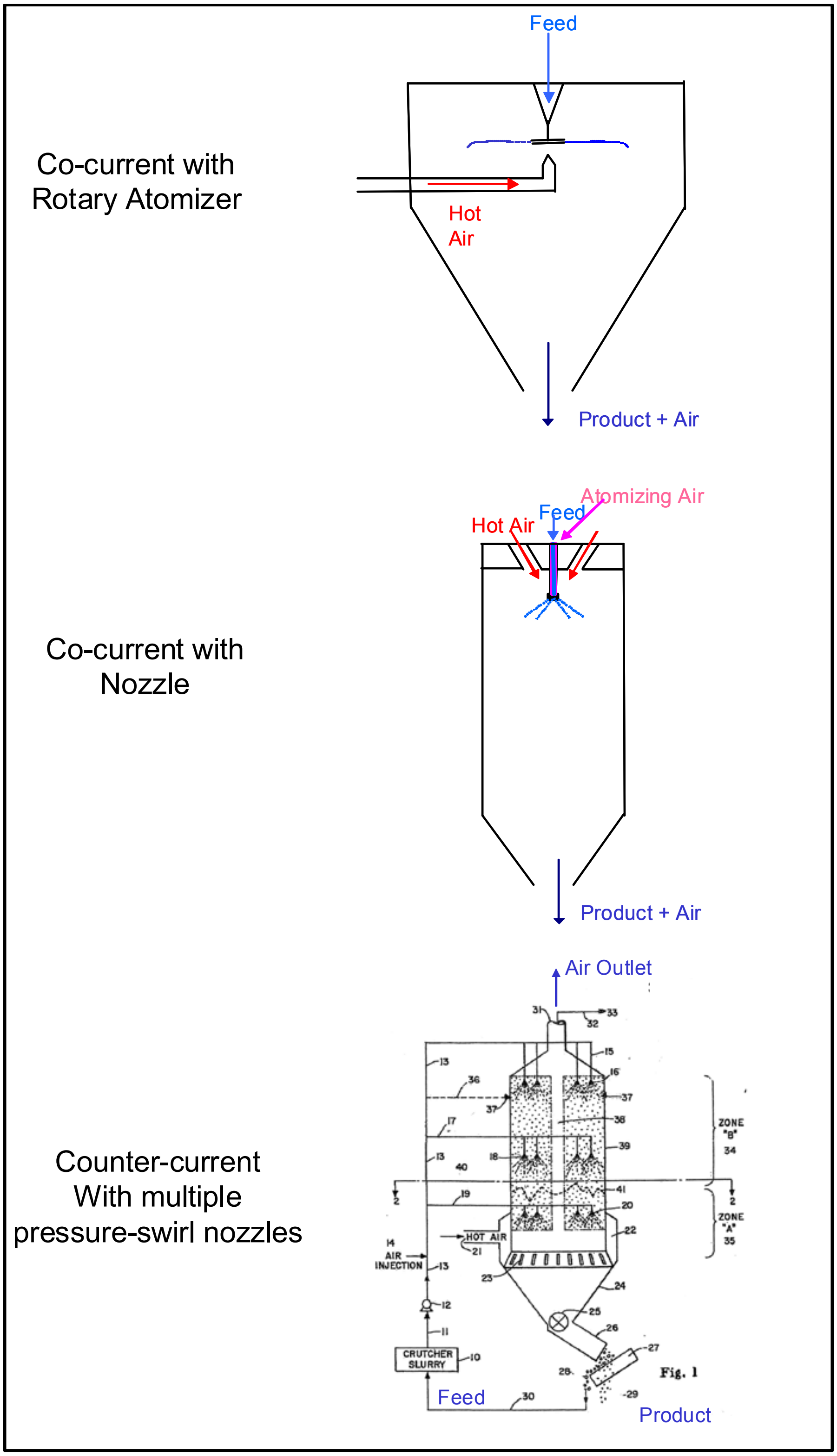

Figure 1. Typical spray dryers. The atomizer type is linked to the geometry. Upper: rotary-style atomizers are used with short and wide drying chambers to minimize wet deposits on the walls. Middle: spray nozzles (either pressure or pneumatic) are typically used with tall and thin dryers. Lower: Nearly all spray dryers are co-current but laundry detergent spray dryers are counter current and contain numerous nozzles [5].

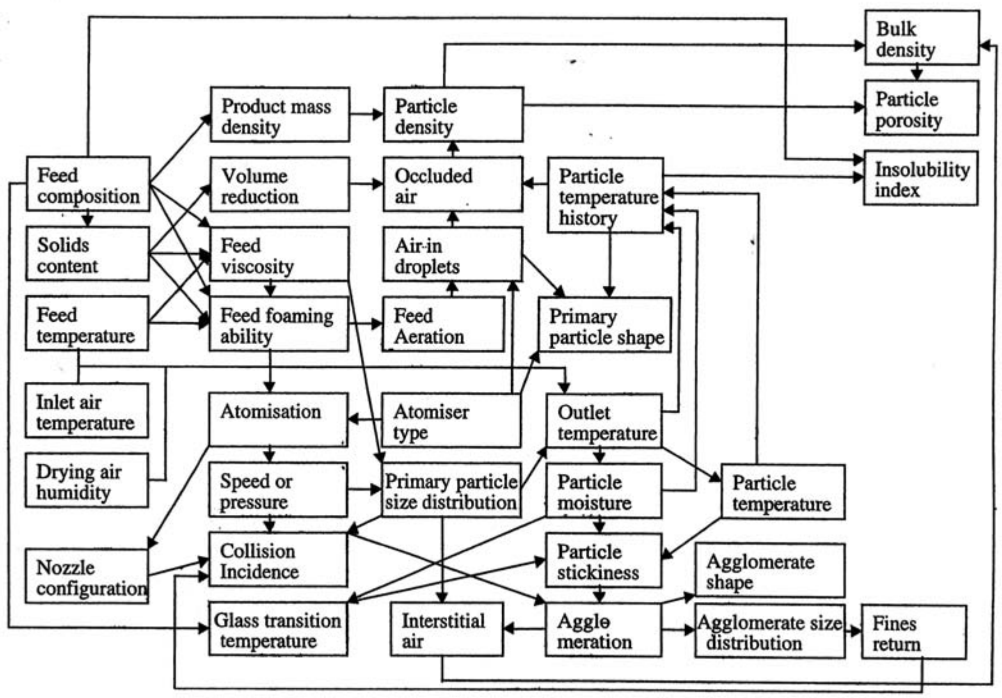

Figure 2. Schematic of complex particle-formation mechanisms occurring within a spray dryer (taken from [10])

Figure 3. Some examples of spray drying atomization experiments at Procter & Gamble. Upper left: a view of our lab during detergent slurry atomization trials. The Oxford laser spray visualization system is shown. Lower left: pneumatic atomization of a proprietary feedstock. Right: detergent slurry flowing through a pneumatic nozzles with the air off. Note the consistency of the material.