

Renewal proposal for IFPRI-Grant

Spray Drying of Pastes with ACLR-Nozzle for Process Intensification

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1 Introduction

Spray drying is a widely used process for the production of powdered products from liquid formulations. The spray drying process can be divided into three main steps: Atomization, convective drying in a hot air stream, and powder separation [1]. As with all drying processes, water removal is a very energy-consuming process, especially as internal-energy recovery is restricted in spray drying [2]. In industrial applications, the aim is therefore to feed the media into the drying process with the lowest possible water content (high dry matter content), allowing for an energy-saving process with a higher product throughput. According to a model calculation on industrial spray drying by Fox et al. [3], an increase in feed dry matter content by 1% leads to a decrease in thermal energy consumption of the spray dryer by 3.8% and to a decrease in total energy consumption of 2.5%. However, the dry mass content cannot be increased at will, since the viscosity of the liquid also increases with increasing solid concentration [4], which may prove challenging during the atomization step. Generally, the atomization of a bulk liquid into small droplets leads to a drastic enlargement of the surface-to-volume ratio, enhancing heat and mass flow in the subsequent convective drying step. At high viscosities, the atomization step becomes more energy intensive, since the volume-specific atomization energy requirement for droplet breakup increases sharply as the internal resistance forces of the liquid increase. This leads to larger droplets and/or wider spray droplet size distributions, up to the point where atomization is no longer possible.

For atomizing highly viscous liquids pneumatic atomizers are usually used. The atomization energy is transferred via a gas stream [5]. While these nozzles have the advantage that the gas and liquid flows can be set independently of each other, they tend to produce wide droplet size distributions unless high rates of atomizing gas are used [6]. This makes the use of external-mixing pneumatic atomizers on an industrial scale not economically feasible. Meanwhile, internal-mixing nozzles promise a more efficient transfer of energy from the gas to the liquid, as a two-phase flow already exits through the nozzle channel. This promises the ability to handle higher-viscosity liquids than with pressure swirl nozzles [7], while using lower rates of atomizing gas than pneumatic atomizers.

The LVT-Institute developed a specific type of internal-mixing nozzle atomizer, the Air-Core-Liquid-Ring (ACLR) atomizer. A schematic of this nozzle can be seen on Figure 1 (left). An experimental high-speed image of the flow inside the nozzle and the computational flow simulations performed are shown on Figure 1 (right).

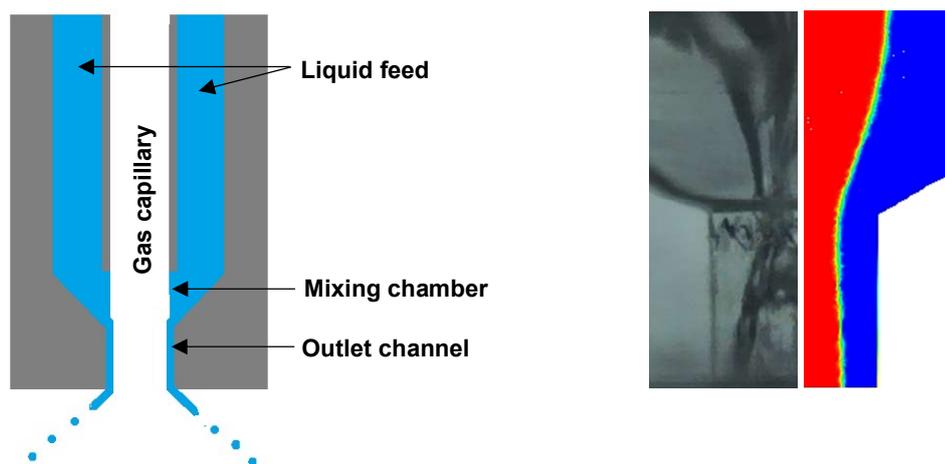


Figure 1: Scheme of the ACLR nozzle (left). Experimental high-speed image of the flow inside the nozzle and the computational simulations performed to represent the internal flow in the atomizer (right)

The device is composed of two concentric tubes. The outer tube is where the liquid feed flows, while a capillary at the center carries the gas and injects it in the center of the mixing chamber. This forms an annular liquid flow, with a gas core. As this two-phase flow exits the nozzle through the outlet channel, the gas phase expands, and the liquid phase forms a cone like lamella that then disperses into droplets. The thickness of the lamella is correlated with the droplet size while the outlet diameter of

the nozzle is much larger, typically larger than 1.5 mm. This nozzle design allows for relatively large particles in the feed stream, as the risk of clogging is low. Before the beginning of the project, the ACLR nozzle has been proven successful for the atomization of highly viscous liquids up to 690 mPa·s [8].

2 Summary of current project

The project made significant advancements in applying the ACLR for spray drying of highly viscous liquids. The main objectives for the first funding period are clustered in three main working packages (WP). **WP 1** aimed to validate the ACLR atomizer technology to enable spraying of highly viscous liquids, using both experimental measurements and CFD simulations. The work on WP 1 has been completed and the results have been presented. The ACLR was proven to achieve stable atomization with feed viscosities of up to 3 Pa·s, at relatively low pressures (7 bar) and low air-to-liquid ratios (< 1). Furthermore, a CFD model was successfully adapted in STAR-CCM+ v.2206 to predict the internal flow of non-Newtonian maltodextrin solutions being atomized with an ACLR nozzle, showing good agreement with experimental data. The possibility of using simulations to evaluate operating conditions outside of experimental capabilities was evidenced. **WP 2** aimed to evaluate the impact of the composition and morphology of the atomized droplets on the drying kinetics, for highly concentrated feeds. For this purpose, a hanging-droplet experimental setup was designed and constructed. A method for the analysis of the mass data and calculation of the drying kinetics was developed. An experimental plan has been laid out, with most of the experimental work finished. The experiments and the data analysis will be completed and presented in the project's third year. The aim of **WP 3** is the investigation of the industrial applicability of the ACLR nozzle for spray drying. This final WP builds upon the main findings of the previous working packages, and an optimized nozzle design is under development, that will be enhanced by geometrical improvements. This should lead to a reduction of the spray droplet size distribution widths, which is a vital step for the subsequent drying step. The simulation plan to optimize the geometrical design of the nozzle has been formulated, and it is currently being carried out. The aim for the current third project year is to finish the simulation plan, as well as the construction and a first evaluation of the new atomizer based on the improved design. This also means, that spray drying trials will not be conducted in this funding period, as challenges during the construction of the single droplet drying tunnel, such as sourcing of components and breaking down of the air heater, lead to delays in the work plan.

3 Objectives of the project renewal

The environmental impact of spray drying can be reduced through process intensification by increasing the concentration of the feed to be dried. Thereby, energy consumption and process carbon footprint can be reduced. This requires the ability to atomize highly viscous liquids, especially pastes. Contradicting descriptions of the defining traits of pastes can be found in literature, and sparked debates during the project's run time. Based on the discussions at the AGM 2023 and AGM 2024, it became apparent that the industry liaisons are looking for systems with two main characteristics when it comes to spray drying of pastes: The system should have a high viscosity (> 1 Pa·s) and it should be a suspension containing particles or fibers of some sort.

For the initial funding period, maltodextrin was agreed upon as a model system, due to its wide range of applications, and the LVT-institute's expertise with the material. Going forward, the adjusted definition of pastes will be considered by investigating a wider range of materials containing particles and fibers. The chosen model systems will be investigated regarding their rheological behavior. Atomization trials will be conducted using the improved ACLR design with all selected model systems. To evaluate the drying behavior of the different systems and identify possible correlations between the morphology development and the drying kinetics, single droplet drying experiments will be carried out and compared to the drying behavior of maltodextrin. Spray drying trials will be conducted in the last project period. The results from the spray drying trials will be used to evaluate the validity of the drying models formulated based on the single droplet drying trials. In summary, key objectives of this project are:

- Extension of the improved ACLR atomizer's applicability to additional systems by defining and characterizing suitable systems including suspensions, and conducting atomization trials.
- Evaluate the impact of the different materials on morphology development and drying behavior and drying models for highly concentrated feeds by single droplet drying.
- Investigation of the applicability of the ACLR nozzle for spray drying of highly viscous pastes

3.1 Methodology and work plan

The project renewal is proposed for two years. The methodology and work plan for the renewal period is presented in the following.

Year one

During the first year of the project's renewal, the focus lies on the evaluation of the improved ACLR atomizer design and the extension of the ACLR atomizer's applicability to additional systems. Based on the discussions from the IFPRI AGMs, several systems were identified that are of interest to the IFPRI industry liaisons. A category of materials that will be considered are food hydrocolloids, such as Gum Arabic (GA), protein or glycoprotein systems. GA dissolves in water to form concentrated suspensions and is commonly used as an emulsifier and thickener. It also has great potential for ensuring food security and promoting sustainable agriculture. Another group of systems are microorganisms such as yeast and prebiotics. Although spray dried yeast is a widely available product, the spray drying process of yeasts and yeast derived products is energy intensive and challenging. Yeast cells are commonly spray dried with dry matter concentrations of around 15 wt%, which provides opportunity for optimization. Cellulose presents an option for fibrous systems, and investigating a salt suspension would be an opportunity of introducing another particulate system into the selection of model systems.

The rheological properties of the selected systems will be characterized using a double gap system (Physica MCR 101/103, Anton Paar, Graz, Austria). To ensure that droplets are produced, which are small enough for spray drying even at high liquid viscosities, atomization trials will be conducted. These trials will be conducted on an atomization rig and spray droplet size distributions will be measured over time using a laser diffraction spectrometer (Malvern Spraytec, Malvern Panalytical Ltd, Malvern, United Kingdom) in a size range of 2-2000 μm .

The drying behavior of the different materials will be investigated using the hanging-droplet setup that was set up during the project's initial funding phase, which is shown in Figure 2. A high-speed camera (IDT Highspeed Os 8 Digitalkamera, Imaging Solutions GmbH, Germany) (1) is used to monitor the droplet size and morphology development, while a flow meter (2) and a PID controlled thermo couple (3 and 6) are utilized to measure the air velocity and temperature, respectively. Drying kinetics are measured with a precision balance (ABP 100-5DM, Kern&Sohn GmbH, Germany) (5). To ensure accurate mass measurements, the balance is mounted on top of a weighing table (4), decoupled from the rest of the experimental setup. A Constellation™ 120E50 5600K LED-light (IDT Europe, Belgium) (7) serves to light the droplet within the drying channel (8). The experimental studies on single droplet drying will focus on the influence of air temperature, air velocity and total solids content on the drying kinetics and morphology development mimicking convective drying. Therefore, the same highly viscous pastes will be used as for atomization. By monitoring droplet size, evaporation rate and temperature profiles of the droplet, the drying kinetics will be determined. For the morphology development, different structural changes are expected. Besides changes in particle size, other phenomena may occur during drying of a droplet. These include the formation of an inhibitory skin, changes in the surface structure (smooth or wrinkled), and rupture of the particle.

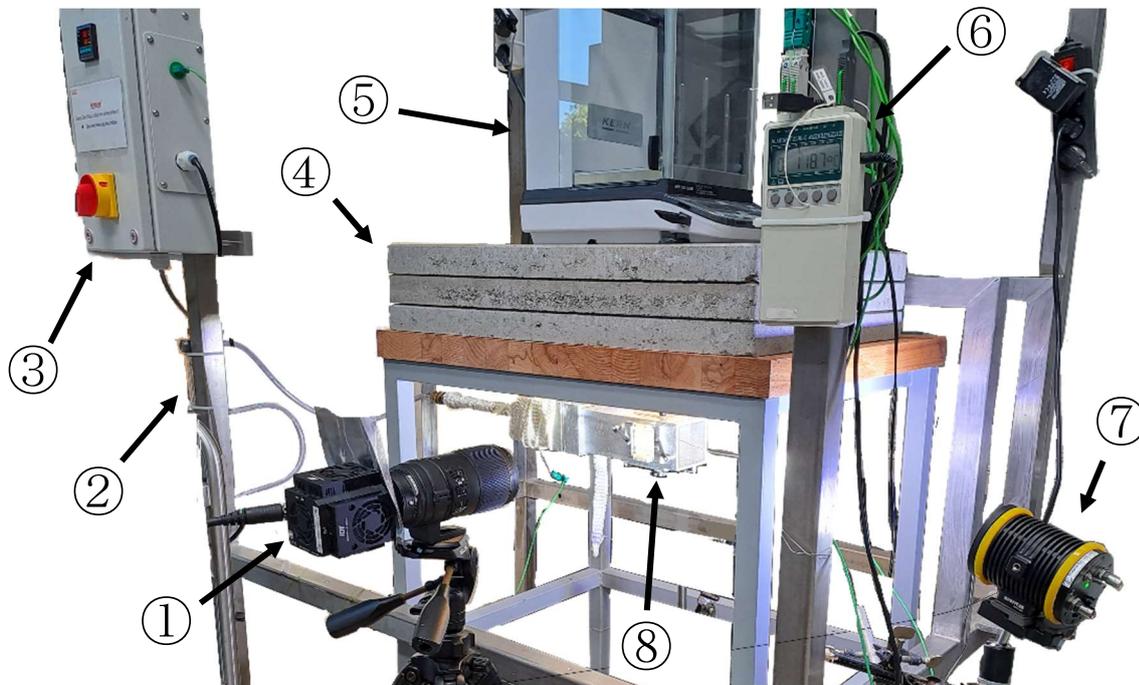


Figure 2: Setup for the hanging-droplet drying experiments: (1) Highspeed-camera, (2) Flowmeter, (3) Control box of the PID controller and the heater, (4) Weighing table reinforced with concrete slabs, (5) Precision balance, (6) Thermo couple at the droplet, (7) Lighting, (8) Drying channel.

Year two

It is expected that conclusions can be drawn from the results of the atomization and single droplet drying trials on possible process windows for atomization and drying conditions of the different systems. The applicability of these conditions on a spray drying process will be investigated. This will represent the main workload during the project's final year. A challenge for the applicability of the ACLR nozzle on spray drying is the material that was used for constructing it. As of now, the outer casing of the ACLR was constructed with clear acrylic. While this allowed the direct optical visualization of the internal flow conditions, it is not suitable for the high drying temperatures of 140–220 °C that are common in spray drying processes. As cooling of the nozzle in the spray tower is not feasible with the current experimental setup, it is expected that fabricating the nozzle out of metal will be the most straightforward solution for this problem. Even though the impact of the material for the outer casing on spray performance is expected to be minimal, select atomization trials will be performed to verify the atomization result. As soon as satisfying results are achieved, the spray drying trials will be executed in pilot scale on the institute's spray dryer (Werco SD-20, Fa. Hans G. Werner, max. water evaporation capacity of 20 l/h, max. air inlet temperature 250 °C, max. air outlet temperature 100 °C). A scheme of the spray dryer is shown in Figure 3.

Initial spray drying trials will be executed using highly viscous maltodextrin solutions, before moving to above mentioned systems containing particles and fibers. Pastes with the highest possible viscosity at acceptable spray droplet size are selected for this purpose. The spray drying experiments can be conducted under variation of the air temperature at the inlet (160–220 °C) and outlet (65–95 °C), the air velocity and the spray droplet size. This way, the drying rate and the surface-to-volume ratio in the particle are varied. The following powder particle properties can be analyzed:

- The particle size distribution will be measured in a laser diffraction spectroscope (LS 13320 Beckman Coulter, Beckman Coulter, CA, USA).
- The residual moisture content will be measured and can be used to validate the drying kinetics determined in single droplet drying.

- The morphology of the produced powder will be characterized and compared to the morphologies that were observed in single droplet drying trials. For this, scanning electron microscopy can be used.

The results allow a validation of the process-structure-functions developed based on the single droplet drying experiments, which will be modified if necessary.

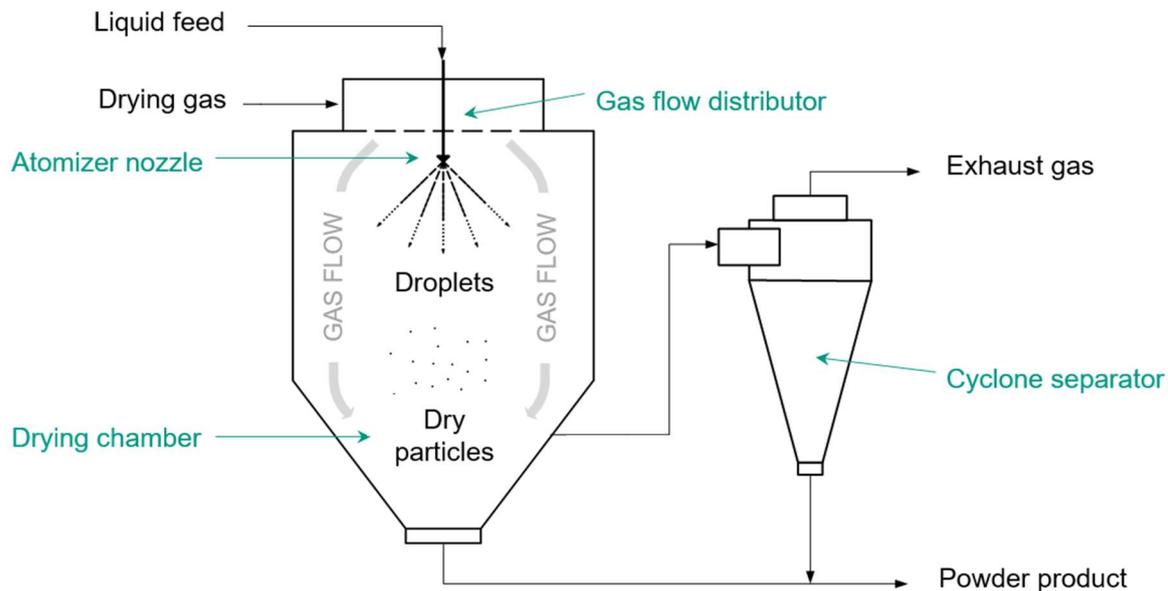


Figure 3: Schematic of the spray drying process

3.2 Transfer of knowledge

The results can be presented and discussed in meetings with the industry liaisons. Based on the results, solution concepts can be derived that contribute to a targeted and understanding-based process design for the production of powder products from highly viscous liquids and pastes. These solution concepts can form the basis for an implementation by the industrial user with their own recipes and processes. The research results can be presented and discussed in accompanying meetings with the industry liaisons and the IFPRI Annual General Meetings during the run time of the project's renewal. The results will be summarized in annual reports. Furthermore, the findings will be presented in suitable international conferences and published in international journals.

4 References

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