VIBRO-PRILLING TO ENHANCE UREA QUALITY

STAMICARBON
NEXTCHEM Sustainable Technology Solutions

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ABSTRACT

Stamicarbon has leveraged its more than 50 years' experience in prilling technology to develop a higher quality prill through the introduction of vibro-prilling technology. While in conventional prilling, thin streams of liquid are created to form droplets which are solidified via convective cooling with counter-current cold air, there is no way to influence jet breakup and droplet formation, the latter being governed by random perturbations.

Vibro-prilling is thus introduced to gain control over the jet breakup mechanics, where well-controlled periodic vibrations (hence the name 'vibro') are added to the liquid flow to induce jet breakup and narrow down the Particle Size Distribution (PSD). This has positive effects on the product and process quality, enhancing heat transfer and leading to less dust emissions since satellite formation, i.e. fine droplets originated after breakup of a tail jet between 2 large droplets, is decreased. This translates into a reduced standard deviation of the PSD, which can in turn be used to shift the distribution to a larger average diameter without generating off-spec material and thus achieving larger and more homogeneous prills.

While vibro-prilling is not a new technology on itself, Stamicarbon and its long-lasting partner Kreber have worked out an innovative and IP protected design that circumvents typical operational problems by transferring the vibrations to the urea melt rather than to the bucket itself, thus drastically reducing maintenance of critical parts such as electromagnets, bearings and the drive.

1 INTRODUCTION

1.1 What is prilling?

Prilling is a process of spray solidification or crystallization which was first used to produce lead shot in 1782 [1]. Nowadays, it is mainly used for the production of urea and ammonium nitrate (AN) fertilizers as well as plastic derivatives and detergents. An illustration of the process and resulting products is given in Figure 1 and 2.

Fig. 1: Illustration of the prilling process.

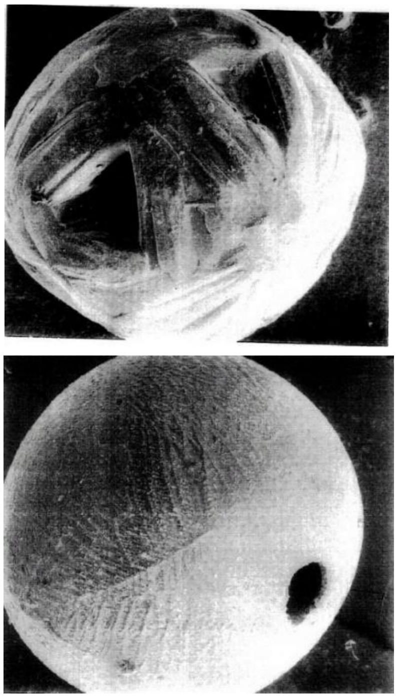

Fig. 2: Hole in prills due to change in the density from liquid to solid.

Pressurized molten material is sprayed through either still nozzles or rotating buckets (commonly referred to as 'static' and 'rotary prillers' respectively) to produce droplets that fall down inside a cooling tower to become solid particles or 'prills'. In other words, bulk amounts of a molten substance are pumped into a bucket (aka the 'priller' or 'prilling bucket') that has nozzles with distinct hole diameters, the latter being the leading parameter determining prill size. With the rotary priller, the bucket spins and causes the jets to spiral out of it to optimize the use of the surface area of the cooling tower. Depending on the desired production rate, this can also be replaced by a static priller. The resulting jets, straight or spiraling, undergo capillary breakup and the resulting droplets fall through the prilling tower, where an upwards stream of cooling air helps these droplets to solidify and form the 'prills'.

The standard urea fertilizer grade prill size is 1.0 to 2.4 mm, with a standard deviation of 15-20%. Particles <1.7 mm are typically categorized as 'fine', 1.7-2.0 as 'medium' and > 2.0 as 'coarse'. However, there is a clear demand of producers for larger prills over the past decades setting the 'medium fraction' (D_{50}) above 2 mm.

1.2 Challenges in traditional prilling

The objective of a good prilling process is to achieve a specific prill size, shape and temperature with minimum OPEX and emissions. Regarding the latter, satellite droplets are fine drops inherently formed after breakup of the thinned tail jet between two larger droplets and are undesired because their small size makes them be carried over by the cooling air becoming a pollutant which must be filtered to prevent particulate matter emission.

Next to that, a common disadvantage of prilling in fertilizers is that the maximum achievable prill is limited by the tower height. This means that a particle with a larger size than the design value will require more cooling, i.e. demanding a longer falling trajectory. Of course, tower height is a fixed parameter after the prill tower is constructed.

If the cooling is insufficient, only partial solidification is achieved by increasing the likelihood of scaling on the walls and the bottom scraper. Moreover, once un-solidified particles reach the bottom, they not only exceed the desired outlet temperature, but also agglomerate forming lumps and posing a handling and quality problem. An example of unsolidified products is shown in Figure 3.

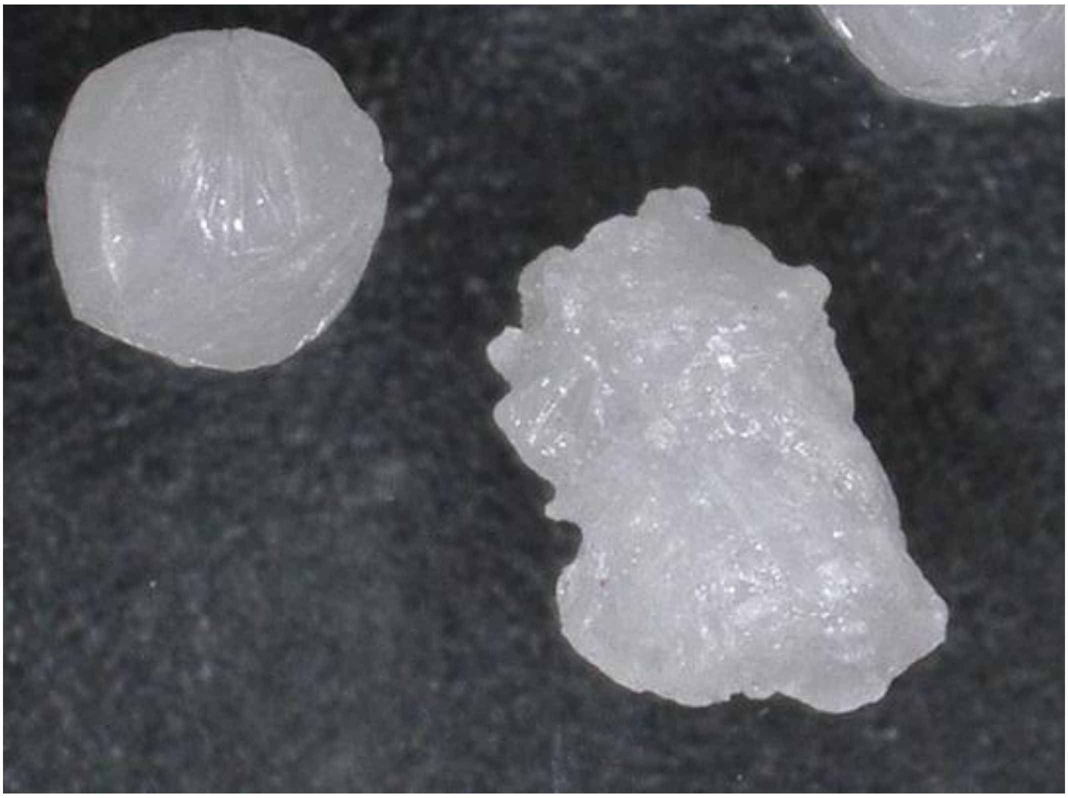

Figure 3: Microscopic image of prills from a process where 25 wt% of material reaches the tower bottom unsolidified. Notice the irregular nonspherical shape of the particle on the right, yielding a product with a low abrasion resistance

1.3 Benefits of narrowing your prill size distribution with vibration

The benefit of a controlled droplet formation in prilling can be illustrated with PSD plots, as shown in *Figure* below. The green section indicates the amount of particulate matter generated from satellite droplets, and the blue section the number of droplets that will not completely solidify in the tower. Partially solidified prills result in scaling and low product quality. The key highlight is that prills produced by a vibro-priller result in a narrower distribution than those manufactured in a conventional way. This means that both the fine (aka ‘particulate matter’), as well as the coarse (aka ‘maximum solidifying particle sizes’) fractions are reduced in favor of particles that are primarily close to the mean value (D_{50}). The overall thermal effect within a prilling tower will also witness an improvement due to the more proportionally sized droplets, yielding the possibility to produce a larger D_{50} as an adequate bucket design will enable shifting the whole distribution to the right-hand side without the risk of generating a larger fraction of over-sized and therefore off-spec particles.

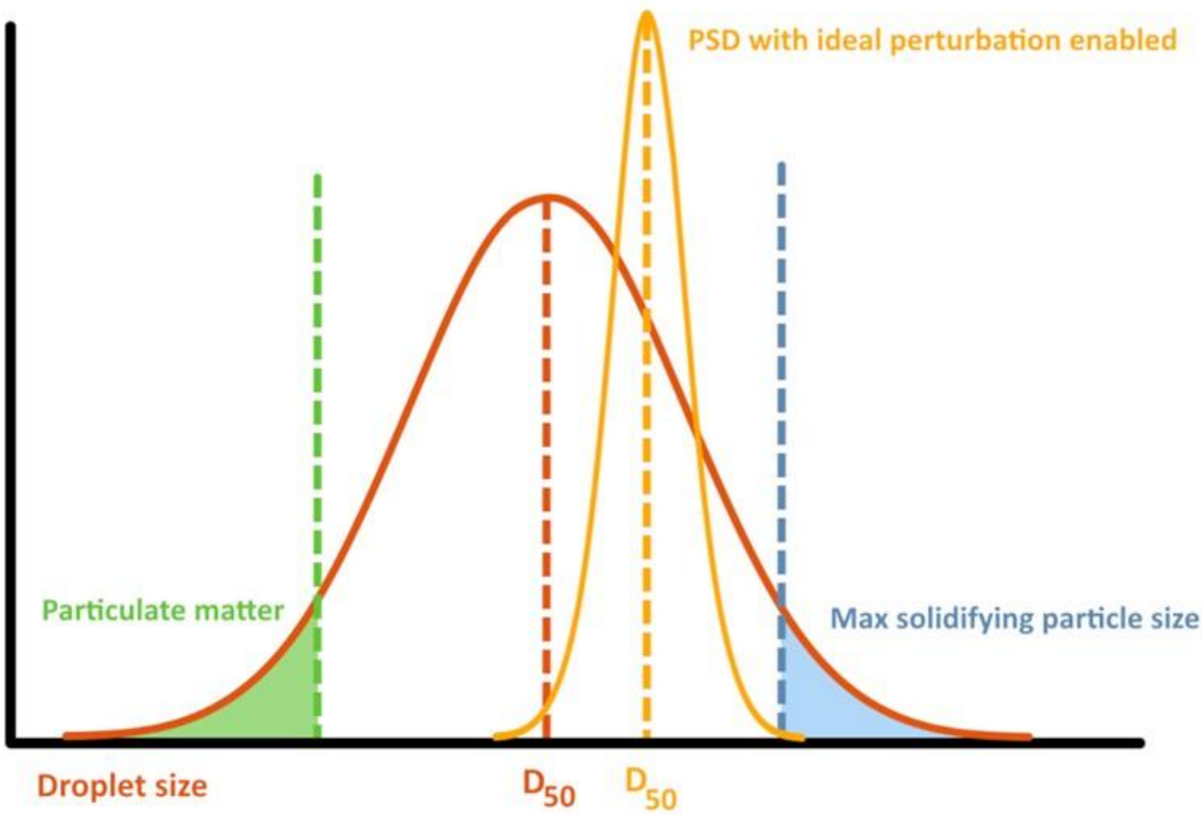

Figure 4: Simulation results of the droplet size distribution with a typical rotary priller (red), compared to a rotary vibro priller (orange)

2 DEVELOPMENT OF VIBRO-PRILLING

2.1. Key scientific challenge: control the Rayleigh-Plateau

Controlling the formation of droplets from liquid jets is a fundamental challenge whose relevance spans applications at a wide variety of scales, from serial femtosecond X-ray crystallography [2,3] where typical jet lengths are on the order of microns, to production of pharmaceuticals [4,5] where it reaches a few tens of millimeters, and to prilling [1] where the jet lengths typically reach a few tens of centimeters. In all these applications, understanding and controlling the breakup is essential. The resulting drop size distribution should be predictable, narrow and monodisperse. If not modulated (i.e., excited with small-amplitude perturbation at a specific frequency), it is irregular with a wide distribution. Among aforementioned applications, control of droplet formation in prilling is particularly challenging and underexplored.

The study of all processes involving jet breakup starts from the well-known Rayleigh-Plateau instability, which manifests itself as a competition of radii of curvatures on a cylindrical column of liquid.

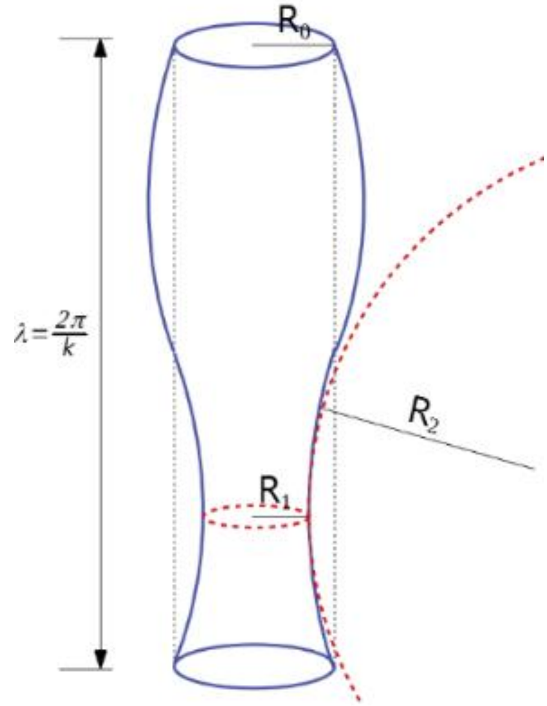

Fig. 5.a: Plateau-Rayleigh jet break-up

Fig. 5.b:: Schematic of a periodic portion of an axisymmetric jet.

It stems from the earlier works of Young and Laplace, who underline the existence of two radii of curvature in a column of liquid and its effect on the pressure p, inside the liquid with γ as the surface tension in N/m.

$$\Delta p = \gamma(\frac{1}{R_1} + \frac{1}{R_2})$$

The above equation formulates the pressure jump due to surface tension in between two mediums across the interface.

Figure 5 indicates the two contributions to curvature. The instability rises from the fact that while the radial curvature (i.e. radius of the jet R1) is always positive, the longitudinal curvature (R2) is negative in the constricted regions and positive in the bloated regions, thus acting both in favor and against the pressure difference. When we consider periodic disturbances with a wavelength and an amplitude on a cylindrical column of liquid, the change of sign of the longitudinal curvature causes some wavelengths to be unstable and others to be stable.

Rayleigh considered the temporal linear stability of an infinite jet in the inviscid limit [6,7]. This was extended by Chandrasekhar by considering the viscous effects [8]. They showed that viscosity slows down growth and increases the wavelength at which the growth is fastest.

After the droplets are formed, the physical problem can be formulated as the crystallization of a droplet that falls through a cooling medium (e.g. air) and loses heat by means of forced convection during crystallization.

2.2. Dynamic behavior: Nonlinear slender jet model

To be able to capture the dynamics close to breakup, e.g. the formation of main and satellite droplets, nonlinear simulations are necessary. Kreber developed an in-house model for jet breakup simulations and utilized it for modelling purposes. Typical results and validation experiments of the model are shown in Figure 6. As an input, two cases are considered, one where jet breakup was first achieved by natural vibration, induced by white noise, and the other where jet breakup is achieved by a dominant vibration tuned on the fastest growing wavelength.

Mechanical vibrations are naturally present in industrial applications of spiraling jets such as in prilling. Even in small-scale laboratory experiments, one can never fully eliminate such vibrations, and they might have a significant effect on the jet breakup. The time series of such noisy perturbations are rather difficult to quantify, however, a good approximation is to represent the vibrations by white noise and to characterize the noise strength in terms of the natural (actuation-free) jet breakup length or breakup time [9]. A comparative image between white noise and vibration dominated break up can be seen in Figure 6 (For further details about the experiments and the simulations, please refer to [10,11])

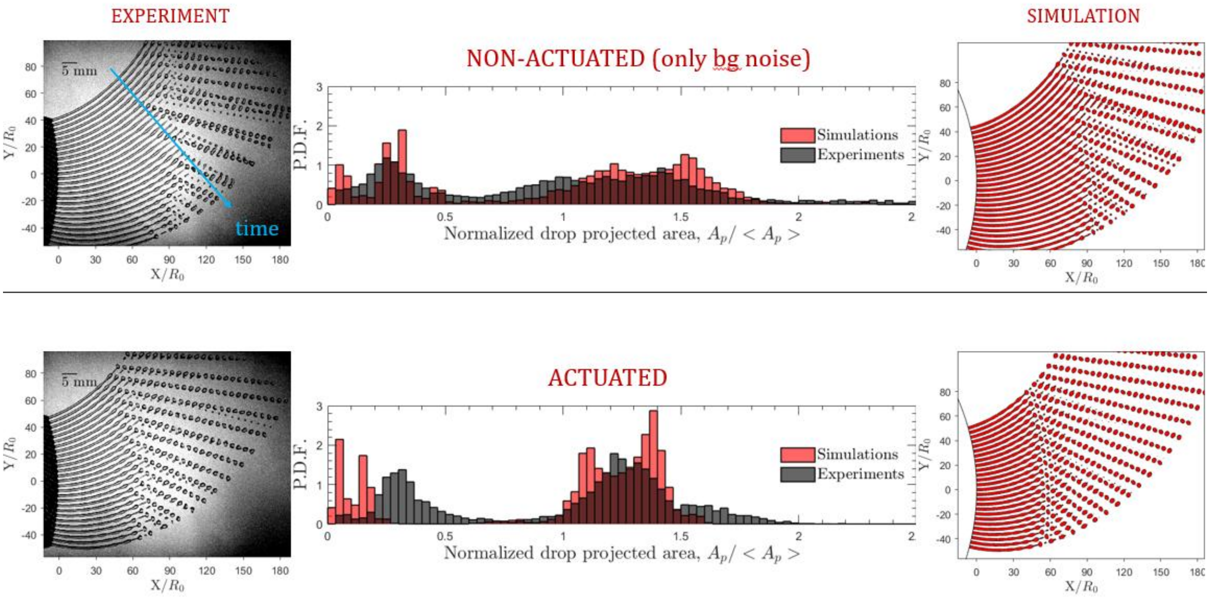

Figure 6: A comparison of lab experiments and simulations, to highlight the effects of vibro actuation. Note that what is shown here is a single jet at different time instants as it passes through our field of view.

Referencing Figure 6, vibro-prilling demonstrates a significant advancement in controlling the jet breakup. In a standard setup, an unperturbed jet leads to a chaotic breakup resulting in a broad range of droplet sizes. However, when vibrational frequencies within the optimal Rayleigh window are applied, the results are transformative. The size distribution of the droplets becomes more defined, typically settling into a bimodal distribution comprising primary and satellite droplets. Close to the nozzle, these satellite droplets tend to merge under the optimal Rayleigh perturbation, resulting in a uniform, monodisperse droplet formation.

The creation of monodisperse droplets significantly enhances product quality, as uniformity in droplet size directly correlates to a more consistent and narrower PSD of the final product. Additionally, the reduction in satellite droplets, a consequence of more controlled jet breakup, minimizes dust formation. Another notable benefit in the process is caused by the droplet size distribution. By narrowing the PSD, the prilling process achieves a more favorable, smaller, surface area-to-volume ratio of the droplets and also leads to a potential for a higher D_{50} value under the same nozzle and operational parameters. Consequently, the overall heat transfer efficiency of the prilling process is increased, marking a notable improvement in both product quality and process efficiency.

3 SCALING-UP VIBRO-PRILLING

As explained in earlier chapters, the lab tests and subsequent dynamic model effectively demonstrate controlled jet breakup on small scale. However, the challenge intensifies when scaling up to an industrial priller, which typically produces thousands of jets simultaneously, aiming for production capacities ranging from 500 to 4000 (MTPD). Achieving uniform dynamics across all jets is crucial to maintain optimal perturbations and consistent prill formation on such a scale.

3.1. Lab scale experiments

Stamicarbon adopted a practical engineering approach to the fundamental challenge by building an experimental setup where a fluid with a controlled hydrostatic height (H) was vibrated at different frequencies and amplitudes and passed through nozzles of different geometries [12]. After recording the resulting droplet sizes, it was found that optimal vibrations leading to equal contraction sections bring homogeneous and satellite free droplets. Furthermore, a mathematical model was built linking the geometry (namely the shape and hole diameter of the nozzle) to the obtained droplet size at different vibration and amplitude ranges to enable optimal design of rotating vibro-prilling buckets at industrial operation conditions.

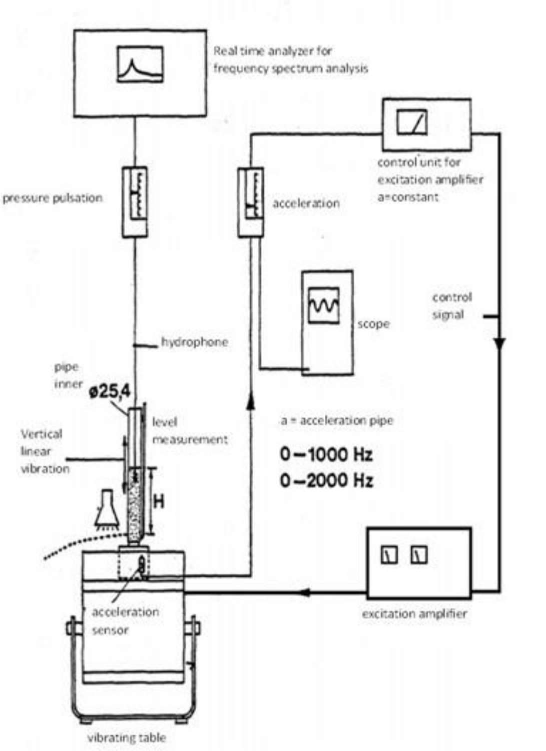

Fig. 7.a: Experimental setup for vibro-prilling

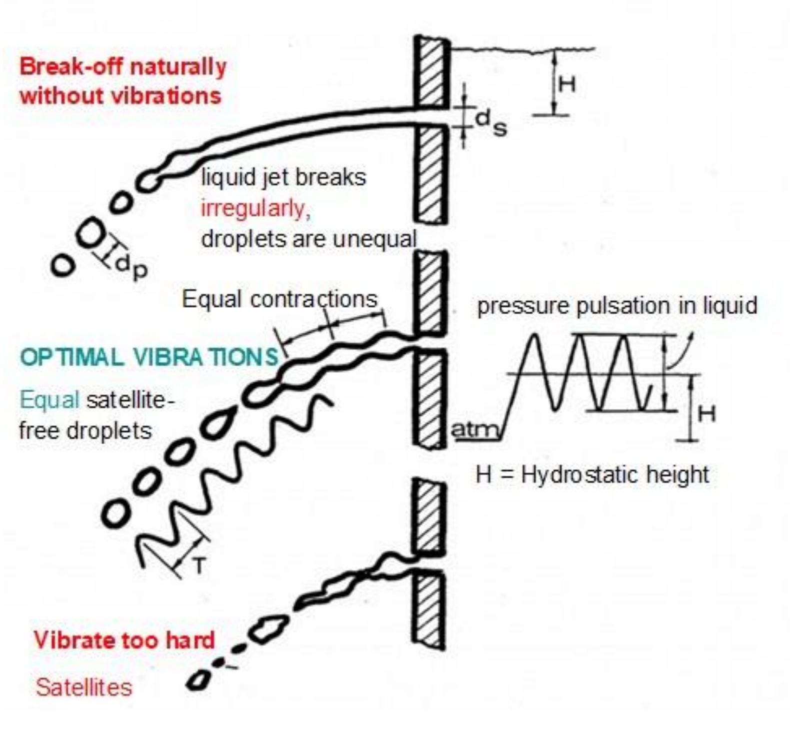

Fig. 7.b: Schematic of results

3.2. Bench scale tests

After the laboratory scale tests, the first bench scale tests were conducted with the initial prototype priller designed with an industrially representative capacity. With these tests Kreber used an in-house developed image analysis tool to detect droplets and compute their size from a given image. This tool helps monitor the improvement in droplet size distribution. Figure 8 shows a typical result obtained from an image taken during drop formation tests. The tool indicates all the droplets with a red box around them and collects statistics from every successive image. The accuracy of the tool also depends on the resolution of the image and the contrast of the subject with respect to the background.

Figure 8: A representative result from Kreber's image analysis tool. The red boxes contain the droplets appearing in the image.

The tests were conducted with a model liquid mimicking molten urea at different amplitudes and frequencies of vibration at industrial capacity of the priller. The optimum frequency for the given priller and the operating conditions are computed using the nonlinear slender jet tool described above. Figure 9 shows the weight-based distribution of the droplets at different amplitudes in comparison to the reference case (i.e. non-vibro breakup).

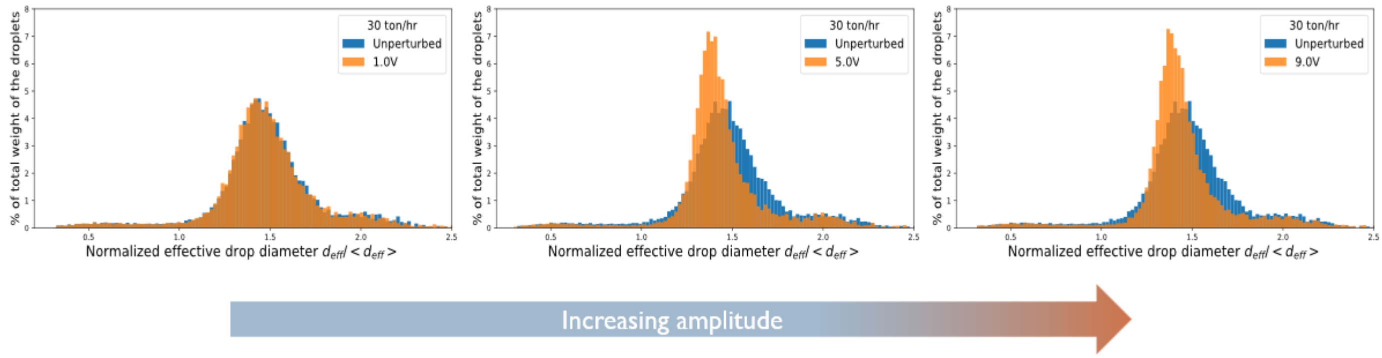

Figure 9: Comparative results of the vibro-prilling test at the optimum frequency at 3 different piezo-amplitudes. Results show that higher amplitudes will lead to a stronger coupling of the perturbations to the jets.

A frequency sweep is also conducted, where the highest possible frequency is kept constant. Figure 10 summarizes the results for 3 different perturbation frequencies around the optimum: Results of the frequency sweep show that while going above the optimum frequency has negligible effect on the results, frequencies lower than the optimum frequency will not improve the drop formation process compared to the unperturbed situation.

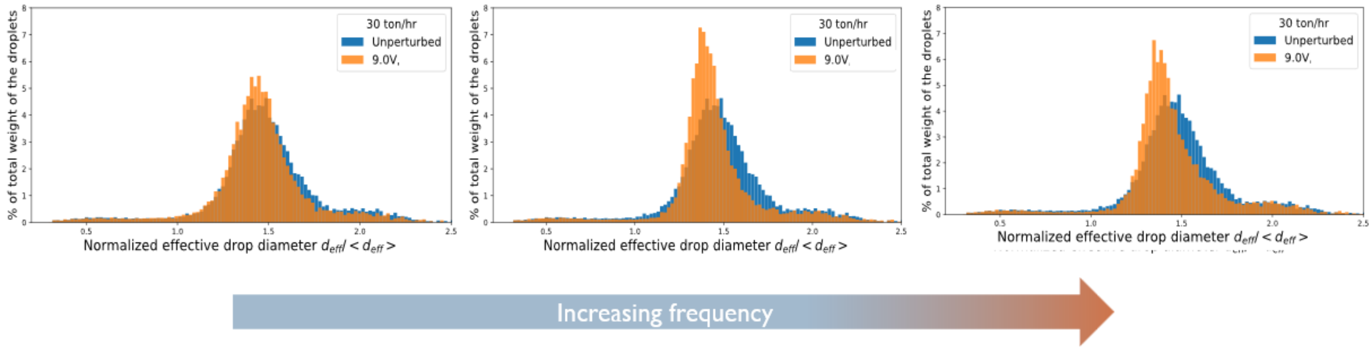

Figure 10: Comparative results of the vibro-prilling test at the highest possible amplitude of 9.0 Volts at 3 different vibration frequencies (orange) compared to the baseline unperturbed (blue).

3.3. Industrial validation

A full-scale urea commercial vibro-priller of 3850 MTPD is on its way to be commissioned in South Asia surpassing the capabilities of existing vibrational prillers in capacity and product quality aspects and demonstrating a significant leap in prilling technology.

4 VIBRO PRILLING AS A REVAMPING TOOL

The implementation of vibro-prilling as a revamping tool, particularly in the urea industry, is a significant step towards enhancing the capabilities of existing prilling facilities. The primary goal of this approach is that the monodisperse droplets leverage the expected improved heat transfer efficiency intrinsic to vibro-prilling. It is expected to have a positive effect on the maximum allowable capacity of current prilling towers, thereby elevating their operational output beyond the limits imposed by traditional prilling methods.

From an environmental standpoint, the reduction in particulate matter emissions is a noteworthy benefit. This aligns with the growing emphasis on sustainable industrial practices, making vibro-prilling an attractive option for industries aiming to minimize their environmental impact.

So, economically, the integration of vibro-prilling into existing facilities is promising. While it's premature to guarantee results, the potential increase in capacity suggests a corresponding rise in revenue, if the prilling section is the bottleneck for further capacity increase, leveraging the existing infrastructure to its fullest potential. Additionally, the efficiency gains from reducing off-spec material contribute to a more cost-effective operation.

One of the key strengths of the Stamicarbon vibro-prilling bucket as a revamping tool is its flexibility. It can be seamlessly integrated into existing prilling machines, offering the versatility to switch between traditional and vibro-prilling modes. This adaptability minimizes operational disruption and risk, allowing for a gradual and optimized transition to a new optimized prilling solution.

Figure 11: Stamicarbon vibro-prilling bucket

Furthermore, because of the patented inner impeller perturbation WO2021/158113, scalability and flexible operating parameters are still available with the vibro-priller, shown in Figure 11. Periods of lower or higher production rates are possible, as low as 60 % of initial capacity and as high as 150 %, where the ideal perturbation is automatically adjusted by the system. Similarly, a production run with the perturbation disabled has no negative impact on the production rate, i.e. the system will operate like a typical rotary priller, ensuring no risk of downtime of the prill production.

5 CONCLUSION

This paper presents a comprehensive exploration of the enhanced control achievable in the prilling process through the innovative application of vibro-prilling on the molten substance. Traditional prilling, while effective, has been limited by its reliance on natural jet breakup and droplet formation, leading to less predictable and wider PSD, and an inefficient material usage due to satellite droplet formation. Vibro-prilling, by introducing controlled periodic fluctuations, offers a significant advancement in this respect by delivering monodisperse droplets that narrow the PSD and minimize the particulate matter production.

The application of vibrational forces within the Rayleigh frequency window to the liquid jets in vibro-prilling demonstrates a marked improvement in controlling the droplet formation. This control is evidenced by the narrower and more predictable PSD, reduction in satellite droplets, and improved heat transfer efficiency. These enhancements not only contribute to higher quality prills by the increased D_{50} and narrower PSD but also promise reductions in material waste and environmental impact.

Furthermore, the development and testing of industrial-scale prototypes indicate the scalability of vibro-prilling technology. While initial tests have shown positive results, challenges remain in uniformly applying perturbations across multiple jets in large-scale operations. The lessons learned from these prototypes have been utilized to design a new prototype with an unprecedented capacity of 3850 MPTD.

Looking forward, the field testing of this new prototype has been a critical milestone to modernize the prilling process by setting new standards for efficiency, control, and capacity. The findings from these tests not only validate the theoretical and experimental work conducted so far but also pave the way for further innovations in prilling technology. Continued research and development in this domain are essential to fully harness the capabilities of vibro-prilling, ensuring its adaptation as a standard practice in industries reliant on prilling for material processing.

In conclusion, vibro-prilling emerges as a promising solution to the longstanding challenges faced in conventional prilling processes. Its ability to enhance control over droplet formation heralds a new era in prilling technology, with significant implications for efficiency, product quality, and environmental sustainability.

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