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Modelling a spray fan of a crop protection sprayer nozzle with the discrete element method

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The testing of application equipment for crop protection products is very laborious due to the field trials usually required. For this reason, the use of simulation methods to reduce the required effort are desirable. To the knowledge of the authors, it has not yet been possible to develop a complete model of a crop protection nozzle and its spray fan. However, models already exist for certain sub-processes such as simulating the drift in computational fluid dynamics (CFD), though these are often not sufficiently validated. Suitable for a complete model is the discrete element method (DEM) i. e. due to the analogy between droplets and simulated particles and the simple contact detection during wetting. The first challenge is the recreation of the spray fan in the DEM, an approach to solve this issue is presented in this article. The simulation model generates a droplet spectrum 100 mm underneath the nozzle based on experiment data. For validation, the droplet spectrum and the transversal distribution are measured 500 mm underneath the nozzle. In the virtual environment the droplet spectrum shows high accordance in comparison to measurements whereas slight deviations in the transversal distribution exist.

Keywords
Discrete element method, DEM, crop protection, droplet spectrum, nozzle, simulation

The testing of crop protection equipment, e. g. in questions of drift behaviour or wetting of the plants during application, is currently usually carried out in very time-consuming and personnel-intensive practical trials. Due to the strong influence of meteorological parameters on the application process, these trials are only reproducible to a limited extent, so that many trials have to be repeated in order to statistically validate the results. In addition, drift tests can only be planned to a limited extent due to the requirements on weather conditions during the test (Julius Kühn-Institut 2013). The measurement of wetting on the plant surface is usually carried out with water-sensitive indicator paper in the crop. Here, effects such as shading by the plant architecture also make reproducibility difficult, so that these experiments can only be carried out with a great effort.

The challenge in the development of technical alternatives for the measurement of characteristics during application is the quantifiability of the measures as well as their validation on the basis of practical data. Empirical measurements of individual test setups are already extended via analytical models (Golla et al. 2011). Numerical simulations are already successfully used for droplet formation and flow from the nozzle (see state of the art). However, the combination with the wetting of the target surface on the plants via suitable simulation methods is not yet part of the research. The dis-

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crete element method (DEM) offers a Lagrangian approach to simulate individual particles and their interactions with each other and the environment. Couplings to fluid dynamics simulations with a complementary Eulerian approach are also possible. Via the contact algorithm, the DEM is suitable for describing the droplet distribution and the localisation of the applied liquid on the target surface. The overall goal is to map the entire application process from droplet formation to wet under realistic environmental conditions with the help of the DEM. Virtual tests can be used to supplement or reduce the time-consuming field trials. In a first step, this article examines the creation of the spray fan in the simulation environment and compares it with practical data from laboratory measurements for validation. In order to represent the droplet spectrum and the transverse distribution in the application plane correctly, a stationary nozzle without additional airflow from headwind or drift should first be investigated and modelled. If the droplet spectrum and transverse distribution are sufficiently accurate represented in the DEM simulation, the next step can be to investigate the nozzle with additional air flows.

State of the art

In crop protection, for each application adapted nozzles exist that are designed to meet different requirements. In the case of hydraulically operating nozzle designs, the droplet formation in the spray fan initially originates from a laminar flow blade which is created at the outlet opening of the nozzle (Figure 1). This then breaks down into individual flowing filaments before these in turn break up into individual droplets of different sizes. Optical measuring systems can detect the individual drops within the spray fan and statistically describe their number and size (Bissell et al. 2014, Vulgarakis Minov 2015, Oxford Lasers 2021).

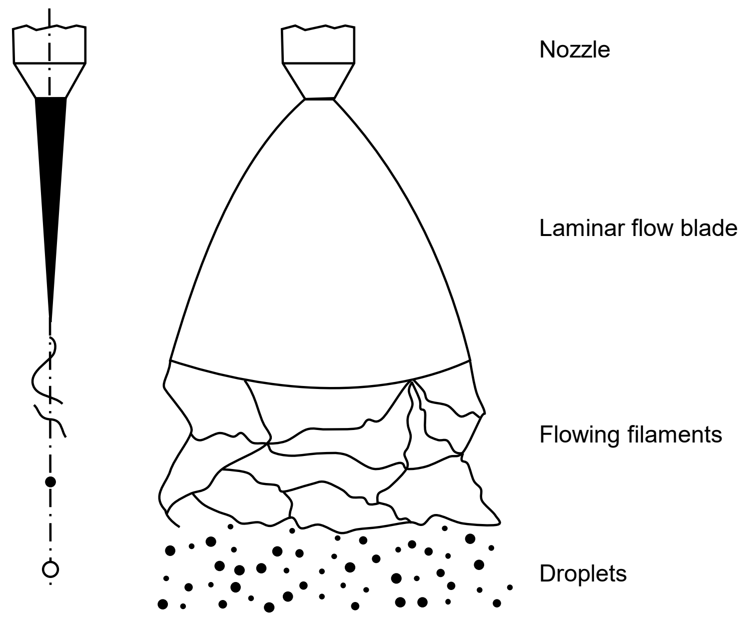


Figure 1: Generation of droplets in planar view after Schmidt (1980)

Transferring such measurements to a simulation has two advantages: Firstly, the results of the simulation can be validated; secondly, the overall process of crop protection application can be broken down into individual sub-processes and individual aspects can be investigated in more detail using simulation. The first two sub-processes are droplet formation and the formation of the spray fan from the moving droplets. The spray fan is influenced by external influences such as (driving) wind or evaporation of individual droplets. The next sub-process is the droplet impact on the plant and the environment. Here, often simplifying assumptions are made and the focus is put on the total amount of applied crop protection products, as the reproduction of the distribution on the surface of the plant is very complex. The last sub-process, namely the wetting of the plant, follows. On the one hand, depending on the surface properties, impact angle, droplet velocity and other parameters, the droplets can either wet or bounce off the surface (Figure 2). On the other hand, droplets that hit already wetted surfaces can roll or drip off them.

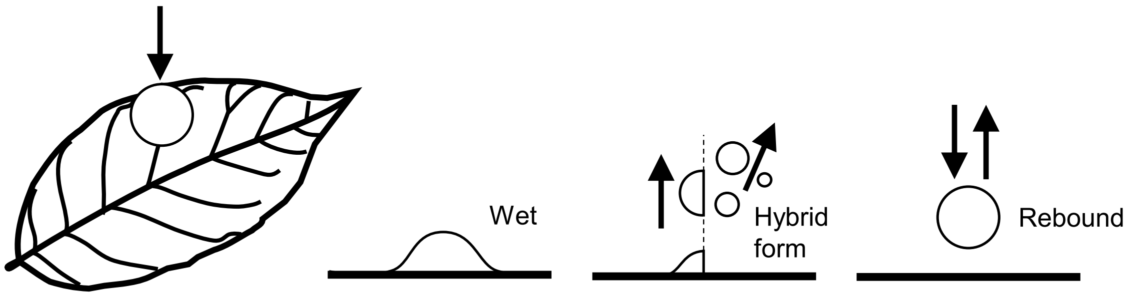


Figure 2: Wetting of plant parts and different bounce behaviour

The sub-processes mentioned have already been simulated individually, whereby applications other than applying crop protection products have been considered in some cases. There are only a few simulation approaches for droplet formation, mostly the simulations of the following processes start with an existing droplet spectrum. Saeedipour investigates and models the droplet formation of two colliding jets in a medical inhaler (Saeedipour 2019). However, the determination of the droplet size only takes place downstream in post-processing. Also in the field of paint spraying technology, the formation of paint droplets in sprayers has been investigated (Shen et al. 2019).

For the simulation of the spray fan and partly also for the consideration of drift and evaporation, mostly mathematical descriptions and empirical models are used (Hobson et al. 1993, Holterman et al. 1997, Holterman et al. 1998b, Holterman et al. 1998a, Dorr et al. 2016, Fujimoto et al. 2016, Cock et al. 2017, Kluza et al. 2019). In addition to the drift caused by air and crosswinds, against the background of applying crop protection products via UAVs, the influences caused by the downwind of the rotors were taken into account. CFD (computational fluid dynamics) simulation approaches are usually used for this purpose (Omar et al. 2016, Fengbo et al. 2017, Yang et al. 2018, Zhang et al. 2018, Parra et al. 2019, Guo et al. 2020, Ni et al. 2021).

CFD simulation is also often used for the sub-process of drop impact on the sprayed surface. In addition to the application of the impact of droplets on plant leaves, which is also considered in this paper and in which different impact and dripping behaviours were taken into account depending on the leaf surface (Delele et al. 2016), the thermal coating of materials was also simulated, in which the droplets can quickly solidify and deform when they hit the surface (Bobzin et al. 2019). By using DEM, the impact behaviour into a comparatively loose particle bed (e. g. sand) was investigated, which is interesting for applied crop protection products that do not contact plant surfaces (Börner und Tsotsas 2013, Börner et al. 2017, LI et al. 2018). For the influence of the impact angle, there is an approach by Mukherjee und Zohdi, who investigated, among others, the adhesion of the droplets on an inclined plane (Mukherjee und Zohdi 2015).

The actual wetting of the surface was investigated simulative primarily in the field of coating and paint spraying technology. For coating tablets or seeds, for example, rotating drums are used into which the coating material is sprayed. DEM simulation is predestined for modelling the particles in the drum. The estimation of the coating of the particles can be done by detecting the time the particles spend in the „spray zone“ (Dubey et al. 2011, Freireich et al. 2011, Kieckhefen et al. 2019). In other approaches, two types of particles are defined for coating. One type forms the material to be coated (A) and the coating material itself is assigned to the second type (B). When particles of type A and B come into contact, the mass of the particle B is added to the mass of the particle A and the particle B is deleted from the simulation (Pasha et al. 2017). The transfer of humidity from one particle to the other during the mixing process can also be simulated (Washino et al. 2016, Schmelzle et al. 2018). In the field of paint spray technology, the use of CFD simulations or formula-based numerical descriptions predominates due to the rigid surfaces that are sprayed and the focus on simulating the spray jet. Simulations are often used here to investigate the influence of the spray angle on the resulting coating thickness, especially for complex shaped components (Fogliati et al. 2006, Ye et al. 2015, Chen et al. 2017, Ye und Pulli 2017, WU et al. 2020). Xie und Wang also consider different pressures of the spray gun (Xie und Wang 2019). From the field of crop protection technology, there are approaches for the mathematical description of the behaviour of the impacting droplets on the leaf (Mayo et al. 2015). By adding chemicals to reduce surface tension, droplet formation on the leaf surface can be avoided and instead a more extensive wetting can be achieved. A more global approach is taken by Hong et al., who use CFD to simulate the spread of crop protection products during application in apple orchards (Hong et al. 2018). However, the wetting of the individual plants is only modelled in a simplified form. A more holistic simulation approach was implemented by Dorr et al. (2016). They consider the application process from the nozzle outlet over the consideration of airflow, evaporation and drift up to the coverage by using plant models. Here, the generated droplets have a random size and a uniform, predefined velocity, resulting in a theoretically uniformly distributed particle density. This approach neglects the inhomogeneity within the spray fan in terms of droplet diameters as well as velocities and thus does not adequately represent the real spray fans of most crop protection spray nozzles. The mathematical relationships were implemented in the L-studio software (Dorr et al. 2008).

It becomes clear that although the individual sub-processes have already been simulated and partially validated with satisfactory results, an overall simulation for the representation of the relationships with the integration of field trial data on the droplet spectrum is still missing. A variety of simulation methods is used to model the individual sub-processes. For the simulation of the spray cone, CFD simulation is often used, which has disadvantages in the contact detection between droplet and plant as well as the representation of wetting. In contrast, both can be modelled well by DEM. As particle simulation method, the DEM is able to calculate the translation and rotation of discrete bodies in three-dimensional space and time-discrete steps according to Newton-Euler equations of motion. The discrete bodies are usually spheres and therefore naturally suitable to simulate droplets. The main advantage of the DEM is the ability to simulate droplets as single, independent moveable particles. Therefore, a holistic model of the spray fan starting after the transition from flow filaments to droplets is possible. Via the interaction of particles (droplets) and geometric elements (application target), the wetting of surfaces can be analysed. A disadvantage compared to CFD is, that flows are difficult to represent in DEM due to the pure interaction between particles or particles and geometries. Although external forces, as they occur through a flow field, can be superimposed on the particles, an interaction for the influences of the particles on the flow is not provided. However, there are many possibilities for extending the DEM and for coupling it with other simulation methods, such as CFD. The DEM therefore provides a basic framework for the simulative investigation of the application of crop protection products. As a first step, the spray cone with real droplet sizes and velocities should be modelled in the DEM, also taking external influencing factors that can lead to drift into account. An approach for this will be presented in the following.

Materials and Methods

In order to simulate the spray fan of a crop protection nozzle and subsequently validate the results obtained, the cone must be measured first. The measurement methods used are presented in the following section. For the DEM simulation, the tool EDEM 2021 (Altair Engineering, Troy (MI), USA) is used, which is then briefly presented.

Measurement of the spray fan

Our analysis of the spray fan includes the measurement of the diameter distribution of droplets as well as the droplet speed and flight angle in dependence of the diameter at various points underneath the nozzle. The droplet spectrum was measured 100 mm underneath the nozzle at discrete points. At this distance to the nozzle opening, the laminar flow blade as well as the flowing filaments visually completely disintegrate to single droplets. The flat fan nozzle TP 11003 S of Teejet was investigated at a pressure level of three bar. We used the Oxford-Laser System (Oxford Lasers Ltd., Didcot, UK) of Julius Kühn Institute (JKI), which is able to measure diameters (from 10 µm), velocity and flight angle of single drops in a field of view of 4 x 3 x 15 mm. The laser system consists of the VisiSize N60 series with the Laser-Power-Unit (LPU) Type 450, a laser head of the Nano-PIV series and its accompanying camera. The droplets to be examined in the spray fan are yielded in the area between the light source (laser head) and the camera and recorded as shadow pattern. The corresponding Software “VisiSize 6” identifies the droplets in the individual exposures and calculates their diameters. The calculation of velocity and flight angle can be done with two images taken at known short time difference.

During measurement, the sprayer nozzle is attached to an in X-Y plane sliding frame and can be moved by servomotors to discrete positions. The nozzle height (Z-Axis) can be adjusted manually. The measurements were done at discrete points. Figure 3 schematically shows the spray fan as well as the measuring points of one quadrant in the X-Y plane. The volumetric distribution at the designated points results from the measurements of the absolute volume distribution in Y-Direction as well as the droplet diameters and numbers at the discrete points. The measurements were conducted in all quadrants with identical settings and then averaged for a single quadrant to eliminate symmetry deviations of the nozzle.

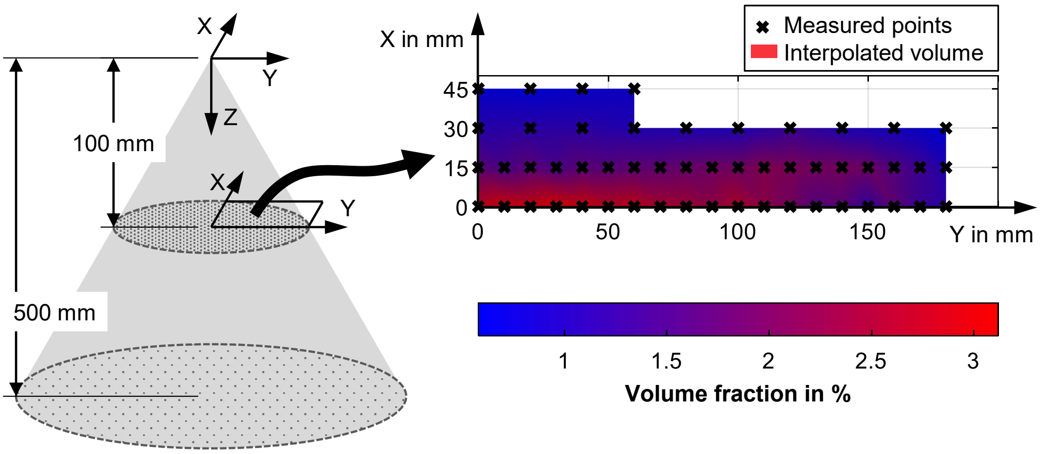


Figure 3: Schematic view of the measuring points in one quadrant of the 100 mm plane

The processing of gathered droplet data (diameter, velocity and flight angle) was done in MATLAB (The MathWorks Inc., Natick (MA), USA). At each measuring point, the diameter distribution as well as the distributions for flight angle and velocity in relation to the diameter were determined. For the diameter distribution, one from 20 distribution functions was selected according to the lowest deviation to the experiment data. The flight angle and velocity were assumed to be normal distributed. The distribution parameters were identified with the maximum-likelihood estimation.

In addition to the study of the droplet analysis, the transverse distribution of the nozzle was determined on the single nozzle gutter test rig with 25 mm resolution of the JKI under the same settings and boundary conditions (Julius Kühn-Institut 2021). In each gutter of the test rig, the applied volume is collected over the test period and can be measured after the experiment. The transverse distribution of the nozzle is assumed to be a normal distribution and can be derived from the measurement data. From the ratio of the summed individual volumes to the duration of the test, the test rig can also be used to determine the absolute flow rate of the nozzle. The investigation of the transverse distribution on the single nozzle gutter test rig was carried out analogously to the measurement of the droplet spectrum at nozzle heights of 100 mm and 500 mm.

The measurement results for the droplet spectrum and the measured transverse distribution in the 100 mm plane are used to build the model. In the validation, the simulated droplet spectrum and the transverse distribution in the 500 mm plane are compared with the test data.

Used Simulation tools

The commercial software EDEM 2021 (Altair Engineering, Troy (MI), USA) is used to model the spray fan in a DEM environment. It offers the necessary flexibility through predefined programmable interfaces (API) and at the same time the necessary computing efficiency for modelling a large number of particles. The additional API model for particle generation is executed once at the beginning of the simulation and reads in a list of particle data for generation. This particle list is generated in advance using MATLAB and includes a predefined number of particles with corresponding diameters, initial velocities and flight angles based on the measured distribution curves, as well as a creation time for each particle based on the specified flow rate. The model for particle generation processes the list and transfers the particles to the simulation environment at the specified creation time. An additional API model influencing the particle force uses a simplified model of fluid drag. This model is called for each particle in each calculation step. The drag force can be calculated from the particle velocity and direction of flight, which is returned to the simulation environment. An additional API model for contact forces is adapted to simulate the wetting of surfaces. This model is usually applied to represent specific contact models and can be implemented for particle-particle contacts as well as for particle-geometry contacts. The model is called for each contact in each calculation step. To wet the surfaces, the contact between a particle and a geometry element is detected and the volume of the particle is transferred to the geometry element. The particle is then removed from the simulation environment. Contact forces between particles and between particles and geometry elements are not calculated. The API models are written in the prescribed language C++ and integrated into the simulation environment as a „dynamic link library" (DLL).

Results

The main result of this research is the developed method for the simulation of the spray fan, which is presented in the following section. The developed model was used to simulate the validation experiments and to generate additional simulation results.

The developed method for the simulation of the spray fan

Figure 4 shows the developed approach using a generic nozzle model to simulate a spray fan in the DEM environment. The generic nozzle model creates droplets in form of particles in the simulation environment. The individual stages are explained in detail below.

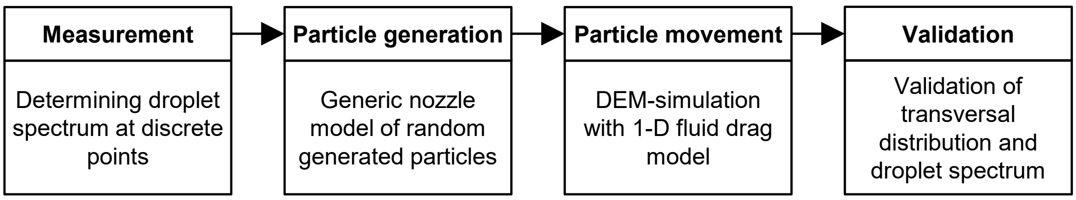


Figure 4: Approach for a simulation model of a spray fan

The generic nozzle model generates particles based on the distribution functions derived from measurement data. Initially, a random Y-coordinate of the range $[0, y_{max}]$ is chosen according to the transversal distribution σ_{Y0} of the nozzle (Eq. 1), at which the corresponding particle is created to represent the droplet.

$$y = \sigma_{Y0} \cdot U(0,1) \quad \text{(Eq. 1)}$$

The elementary shape of the spray fan is assumed to be an idealised ellipse. Subsequently, to generate the elliptical shape, the lateral distribution in X-direction σ_X is scaled depending on the Y-coordinate and the maximum spread y_{max}.The maximum lateral distribution σ_{X0} is given for the position centered under the nozzle.

$$\sigma_X(y) = \sqrt{\left(1 - \frac{y^2}{y_{max}^2}\right) \cdot \sigma_{X0}^2} \quad \text{(Eq. 2)}$$

Using the transversal distribution $\sigma_X\ (y)$ at the Y-Position, a random X-coordinate is chosen analogue to Eq. 1. Figure 5 shows the resulting initial points of the droplet particles in the simulation. The particle density of the individual area elements is given normalised to the total number of particles. A higher particle probability in the centre of the nozzle and continuous decrease in X- and Y- direction can be noticed.

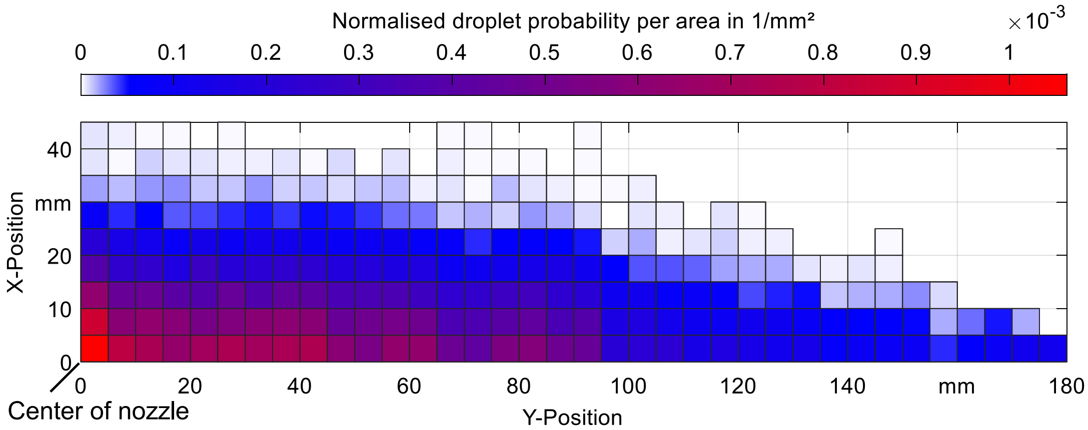
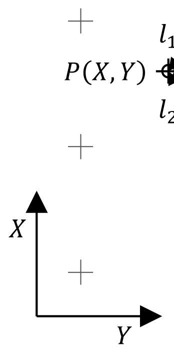


Figure 5: Simulated particle frequency in the 100 mm plane of 1/4th of a nozzle

After determination of the X- and Y-Position of the droplet particle, the closest two measuring points are selected as supporting points S_1 and S_2 for interpolation (Figure 6). According to the two diameter distributions of the supporting points, two random diameters d_1 and d_2 are chosen. The distances l_1 and l_2 between particle position and supporting points are used as weights to calculate the mean diameter d as the particle diameter. For this particle diameter, the flight velocities v_1 and v_2 as well as angles α_1 and α_2 are selected according to the distributions of the corresponding supporting points. Analogue to the determination of the particle diameter d, the distances to the supporting points are used as weights to calculate the particle velocity v and flight angle α. Finally, the initial droplet properties are fully determined and the next droplet is generated according to these distributions. In order to give a qualitatively correct droplet spectrum with an acceptable calculation time, the simulation model generates a droplet number of 20000 particles.



$$d(S_1, S_2) = \frac{d_1(S_1) \cdot l_2 + d_2(S_2) \cdot l_1}{l_1 + l_2}$$

$$\alpha(S_1, S_2, d) = \frac{\alpha_1(S_1, d) \cdot l_2 + \alpha_2(S_2, d) \cdot l_1}{l_1 + l_2}$$

$$v(S_1, S_2, d) = \frac{v_1(S_1, d) \cdot l_2 + v_2(S_2, d) \cdot l_1}{l_1 + l_2}$$

Figure 6: Calculation of particle properties using supporting points

In the following, the particle movement in the DEM is described. A gravitational force and a one-dimensional fluid drag model influence the movement, which enables a realistic behaviour of the particles in the surrounding air.

The gravitation g acts as continuous acceleration in Z-direction on the particles (particle mass m_P, gravitational force F_Z).

$$F_Z = m_P \cdot g \qquad \text{(Eq. 3)}$$

The fluid drag model of HOLTERMAN et al. is utilised (HOLTERMAN et al. 1997). This model uses an empirical calculation of the fluid drag coefficient c_w based on the Reynolds number of the droplets R_e, which results from the relative velocity v_r, the air density ρ_L and the particle diameter d_P.

$$R_e = |\vec{v_r}| \cdot \rho_L \cdot \frac{r_P}{18.2 \cdot 10^{-6}} \qquad \text{(Eq. 4)}$$

$$c_w = \left[\left(\frac{24}{Re}\right)^{0.52} + 0.553\right]^{1.923} \qquad \text{(Eq. 5)}$$

The fluid drag force F_S is calculated from the relative velocity, the fluid drag coefficient, the particle radius and the air density. As effective drag cross-section area, a circular area with the particle radius is assumed. .

$$\vec{F_S} = 0.5 \cdot \vec{v_r} \cdot |\vec{v_r}| \cdot c_w \cdot \pi \cdot r_P^2 \cdot \rho_L \qquad \text{(Eq. 6)}$$

The relative velocity is derived from the particle velocity $\vec{v_P}$ and a modifiable, superimposed airflow velocity $\vec{v_S}$, which enables a simplified simulation of an airstream or a drift.

$$\vec{v_r} = \vec{v_S} - \vec{v_P} \qquad \text{(Eq. 7)}$$

The new developed, specific contact model to simulate the wetting does not calculate contact forces between particles or between particles and geometries. Instead, it calculates an equivalent film thickness for geometry-elements in case of a contact between particles and geometry-elements.

The particle volume is distributed evenly and completely over the geometry-element and the particle will subsequently be deleted from the simulation environment. The film thickness of a geometry-element is accumulated when it is hit by multiple particles. The implementation of droplet rebound or dripping would be possible in principle (Figure 2), but needs to be researched in detail first.

For verification and validation of the spray fan model, a stationary nozzle without airstream or headwind was modelled analogue to the corresponding experiments. Particle generation is performed once at time t = 0,0 s in the plane 100 mm underneath the nozzle, and only a quarter of the spray fan is simulated. To verify the particle generation, the particles generated in the simulation are compared with the measurements of the droplet spectrum (particle number and diameter) and the transverse distribution (particle volume) 100 mm below the nozzle. The objective of the simulation is the correct representation of the spray fan, which can be characterised by the droplet spectrum and the transverse distribution in a plane 500 mm below the nozzle. The particle number/diameter respectively volume distributions in this plane are therefore used to validate the simulation of the spray fan. The evaluation of transversal distribution is carried out when all particles deposited on the application plane.

Simulation results

The simulation model consists of the developed nozzle model, which generates the particles 400 mm above a panel representing the application surface, and thus corresponds to the experimental setups. Figure 7 shows different moments in the simulation. It is observable, that 0.1 s after particle generation, all large and fast particles have already reached the application plane and have applied the mayor part of the total volume. The smallest and therefore by the fluid drag heavily effected particles need at least t = 40 s to sink to the application plane. The transverse distribution is determined by the simulated wetting of the plate, for verification this was moved to the creation plane.

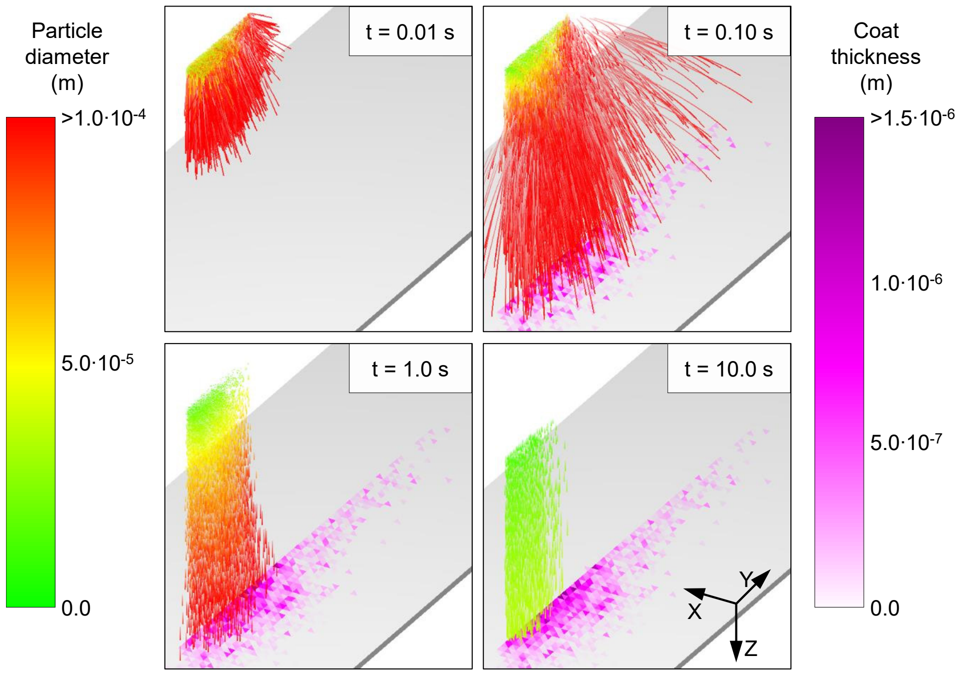


Figure 7: Simulated wetting of the application plane with 1/4th of a nozzle

Figure 8 compares the transversal distributions of experiment and simulation in the generation plane (Z = 100 mm) as well as in the application plane (Z = 500 mm). In the generation plane, the simulation shows good correlation with the test results. In the application plane, the model almost reaches the same half spread width of ca. 750 mm. The applied volume in the simulation is higher directly underneath the nozzle and in return lower in a distance of 250–750 mm from the nozzle compared to the experiment.

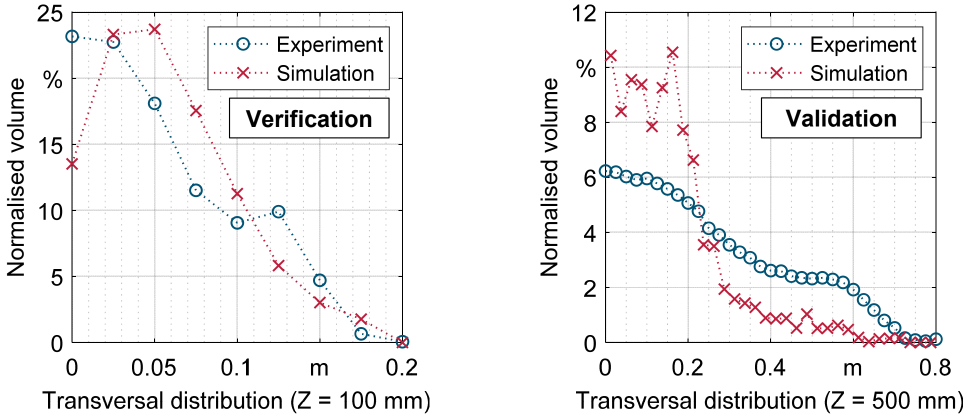


Figure 8: Comparison of the transversal distribution in Y-Direction of experiment and Simulation

In addition to the transverse distribution, the droplet spectrum centrally below the nozzle can also be investigated as a validation parameter (Figure 9). In the generation plane, the droplet spectrum is sufficiently well reproduced with a slight trend towards smaller droplets. In the application plane, the number of smallest particles with diameters ranging from 0–50 µm is significantly higher in the simulation compared to the experiment. The number of particles with a diameter of 50–200 µm is correspondingly lower.

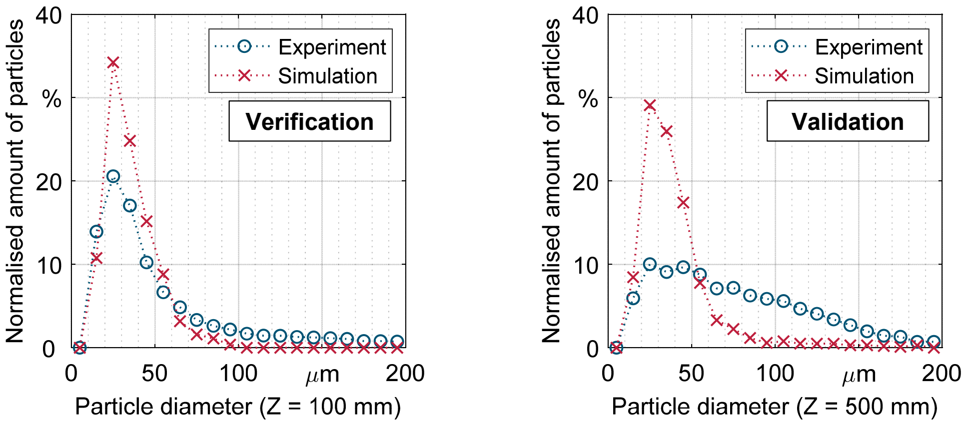


Figure 9: Comparison of the droplet spectrum centric underneath the nozzle

In Figure 10, in addition to the validation simulations, an overall simulation of the application process was performed, taking drift and wetting into account. The droplet movement was simulated for a uniform head wind of 2 m/s. A superimposed vector in X-direction in the fluid drag model implements the head wind. The plants are imported in the simulation environment as fixed geometries. The wetting of plants can thus be investigated as film thickness via the specific contact model.

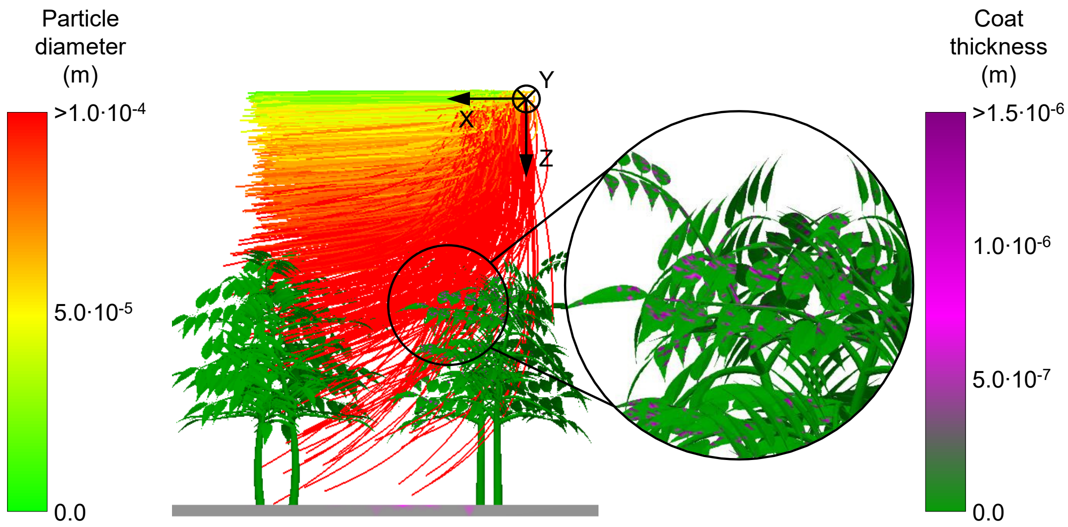


Figure 10: Use of the simulation model to investigate the drift and wetting

Discussion

The objective of the conducted work was to create the spray fan of a crop protection spray nozzle in the DEM simulation environment on the basis of measured data and a subsequent validation. For the final evaluation of the developed method, the simulation results obtained are discussed below. Subsequently, potentials for the further development of the model will be identified.

The comparison of the simulation results with the experiment results in the droplet generation plane shows good agreement both in the transverse distribution and in the droplet spectrum, see Figure 8 and Figure 9 on the left. The droplet generation is thus verified. For the validation, the results of both the experiments and from the simulation are evaluated at the application level 500 mm below the nozzle. In contrast to the generation level, there are deviations in the transverse distribution as well as in the droplet spectrum. One reason for these deviations could be the self-induced airstream, which results from the fast movement of large droplets. With the impact of the stream on the application plane in the experiments and due to the velocity difference between the spray fan and the surrounding air, vortices are built up inside the spray fan, which carry medium and small particles further outwards. This would explain the deviations in the drop spectrum centrally below the nozzle (see Figure 9). In the outmost area, this thesis can neither be confirmed nor refuted due to the low total number of particles in the experiments. The nozzle TP11003 of TeeJet in this research has a fine droplet spectrum and is used by the JKI as reference for drift experiments. Due to the fine droplet spectrum, a simulation of this nozzle is more challenging than that of a nozzle with larger droplets, since large droplets are less effected by fluid drag, as shown in the measurements.

Conclusion

As a result, it can be stated that the simulation model can already be used for the visualisation and simplified investigation of drift and wetting, as demonstrated in Figure 10. Due to the existing deviations from the experiments, the model is not yet fully validated; for this, the flows in the spray fan must be investigated in more detail and implemented in the model. The successful generation of the spray fan is an important step towards a complete model for simulating crop protection nozzles, although further development is still required. The droplet generation, which currently takes place 100 mm below the nozzle, should be extrapolated to the outlet point of the nozzle. In this way, external influences such as driving wind and crosswind, which can also act on the laminar flow blade and flowing filaments in the first 100 mm underneath the nozzle, are to be taken into account. The DEM is not the appropriate tool for simulating such flows, therefore a coupling with a CFD simulation will be implemented in the next step.

For the further development of the model, the process of drift should be investigated and implemented more differentiated by adding a laterally acting force directly into the DEM environment. If necessary, the CFD coupling used for the self-induced flows can also be used for modelling the drift. Further challenges in the simulation of drift are the effects of droplet decay, droplet agglomeration and evaporation, occurring increasingly with external forces. The further developed models are to be validated using empirically obtained measurement data. The drift mainly affects the smaller droplets, making comparative measurements more difficult. Suitable measurement methods are to be identified and implemented. For this purpose, the wind tunnel at the JKI provides a possibility for reproducible experiments on the drift behaviour of nozzles. With a successful validation of the drift behaviour, it can be assumed that the simulation model represents the spray fan sufficiently accurate for further investigations.

The model will then be successively extended to include the other process steps, in particular the impact on plants or the environment and the resulting wetting. Finally, an overall model is to be created with which the time-consuming field trials with crop protection nozzles can be reduced and the knowledge gained can be expanded.

References

Bissell, D.; Lai, W.; Stegmeir, M.; Troolin, D.R.; Pothos, S.; Lengsfeld, C.S. (2014): An Approach to Spray Characterization by Combination of Measurement Techniques. In: ILASS Americas 26th Annual Conference on Liquid Atomization and Spray Systems, Mai 2014, Portland

Bobzin, K.; Öte, M.; Knoch, M.A.; Alkhasli, I.; Dokhanchi, S.R. (2019): Modelling of particle impact using modified momentum source method in thermal spraying. IOP Conference Series: Materials Science and Engineering 480, https://doi.org/10.1088/1757-899X/480/1/012003

Börner, M.; Bück, A.; Tsotsas, E. (2017): DEM-CFD investigation of particle residence time distribution in top-spray fluidised bed granulation. Chemical Engineering Science 161, pp. 187–197, https://doi.org/10.1016/j.ces.2016.12.020

Börner, M.; Tsotsas, E. (2013): Spray zone demarcation in top-spray fluidised bed granulation by droplet detection methods. In: 6th International Granulation Workshop, June 2013, Sheffield, UK

Chen, Y.; Chen, W.; Li, B.; Zhang, G.; Zhang, W. (2017): Paint thickness simulation for painting robot trajectory planning: a review. Industrial Robot: An International Journal 44(5), pp. 629–638, https://doi.org/10.1108/IR-07-2016-0205

Cock, N. de; Massinon, M.; Salah, S.O.; Lebeau, F. (2017): Investigation on optimal spray properties for ground based agricultural applications using deposition and retention models. Biosystems Engineering 162, pp. 99–111, https://doi.org/10.1016/j.biosystemseng.2017.08.001

Delele, M.A.; Nuyttens, D.; Duga, A.T.; Ambaw, A.; Lebeau, F.; Nicolai, B.M.; Verboven, P. (2016): Predicting the dynamic impact behaviour of spray droplets on flat plant surfaces. Soft matter 12(34), pp. 7195–7211, https://doi.org/10.1039/c6sm00933f

Dorr, G.; Hanan, J.; Adkins, S.; Hewitt, A.; O'Donnell, C.; Noller, B. (2008): Spray deposition on plant surfaces: a modelling approach. Functional plant biology : FPB 35(10), pp. 988–996, https://doi.org/10.1071/FP08056

Dorr, G.J.; Forster, W.A.; Mayo, L.C.; McCue, S.W.; Kempthorne, D.M.; Hanan, J.; Turner, I.W.; Belward, J.A.; Young, J.; Zabkiewicz, J.A. (2016): Spray retention on whole plants: modelling, simulations and experiments. Crop Protection 88, pp. 118–130, https://doi.org/10.1016/j.cropro.2016.06.003

Dubey, A.; Hsia, R.; Saranteas, K.; Brone, D.; Misra, T.; Muzzio, F.J. (2011): Effect of speed, loading and spray pattern on coating variability in a pan coater. Chemical Engineering Science 66(21), pp. 5107–5115, https://doi.org/10.1016/j.ces.2011.07.010

Fengbo, Y.; Xinyu, X.; Ling, Z.; Zhu, S. (2017): Numerical simulation and experimental verification on downwash air flow of six-rotor agricultural unmanned aerial vehicle in hover. International Journal of Agricultural and Biological Engineering 10(4), pp. 41–53, https://doi.org/10.25165/j.ijabe.20171004.3077

Fogliati, M.; Fontana, D.; Garbero, M.; Vanni, M.; Baldi, G.; Dondè, R. (2006): CFD simulation of paint deposition in an air spray process. Journal of Coatings Technology and Research 3(2), pp. 117–125, https://doi.org/10.1007/s11998-006-0014-5

Freireich, B.; Li, J.; Litster, J.; Wassgren, C. (2011): Incorporating particle flow information from discrete element simulations in population balance models of mixer-coaters. Chemical Engineering Science 66(16), pp. 3592–3604, https://doi.org/10.1016/j.ces.2011.04.015

Fujimoto, A.; Satow, T.; Kishimoto, T. (2016): Simulation of spray distribution with boom sprayer considering effect of wind for agricultural cloud computing analysis. Engineering in Agriculture, Environment and Food 9(4), pp. 305–310, https://doi.org/10.1016/j.eaef.2016.04.001

Golla, B.; Strassemeyer, J.; Koch, H.; Rautmann, D. (2011): Eine Methode zur stochastischen Simulation von Abdriftwerten als Grundlage für eine georeferenzierte probabilistische Expositionsabschätzung von Pflanzenschutzmitteln. 33-44 Pages / Journal für Kulturpflanzen, Vol. 63 No. 2 (2011), https://doi.org/10.5073/JfK.2011.02.02

Guo, Q.; Zhu, Y.; Tang, Y.; Hou, C.; He, Y.; Zhuang, J.; Zheng, Y.; Luo, S. (2020): CFD simulation and experimental verification of the spatial and temporal distributions of the downwash airflow of a quad-rotor agricultural UAV in hover. Computers and Electronics in Agriculture 172, https://doi.org/10.1016/j.compag.2020.105343

Hobson, P.A.; Miller, P.; Walklate, P.J.; Tuck, C.R.; Western, N.M. (1993): Spray Drift from Hydraulic Spray Nozzles: the Use of a Computer Simulation Model to Examine Factors Influencing Drift. Journal of Agricultural Engineering Research 54(4), pp. 293–305, https://doi.org/10.1006/jaer.1993.1022

Holterman, H.J.; Michielsen, J.; van de Zande, J.C. (1998a): Spray drift in crop protection: validation and usage of a drift model. Paper no. 98-A-012, 24.-28.08.1998, Oslo

Holterman, H.J.; van de Zande, J.C.; Porskamp H.A.J.; Huijsmans, J. (1997): Modelling spray drift from boom sprayers. Computers and Electronics in Agriculture 19, pp. 1–22

Holterman, H.J.; van de Zande, J.C.; Porskamp H.A.J.; Michielsen, J. (1998b): IDEFICS: a physical model of spray drift from boom sprayers in agriculture. In: ILASS Europe, Institute for Liquid Atomization and SpraySystems; The Atomization and Sprays Research Group UMIST, 6.-8.7.1998, Manchester, pp. 493–498

Hong, S.-W.; Zhao, L.; Zhu, H. (2018): CFD simulation of pesticide spray from air-assisted sprayers in an apple orchard: Tree deposition and off-target losses. Atmospheric Environment 175, pp. 109–119, https://doi.org/10.1016/j.atmosenv.2017.12.001

Julius Kühn-Institut (2013): JKI-Richtlinie 7-1.5 für die Prüfung von Pflanzenschutzgeräten. Messung der direkten Abdrift beim Ausbringen von flüssigen Pflanzenschutzmitteln im Freiland, Braunschweig

Julius Kühn-Institut (2021): Institut für Anwendungstechnik im Pflanzenschutz. Geräte und Ausstattungen. https://www.julius-kuehn.de/at/geraete-und-ausstattungen/, accessed on 15 July 2021

Kieckhefen, P.; Lichtenegger, T.; Pietsch, S.; Pirker, S.; Heinrich, S. (2019): Simulation of spray coating in a spouted bed using recurrence CFD. Particuology 42, pp. 92–103, https://doi.org/10.1016/j.partic.2018.01.008

Kluza, P.A.; Kuna-Broniowska, I.; Parafiniuk, S. (2019): Modeling and Prediction of the Uniformity of Spray Liquid Coverage from Flat Fan Spray Nozzles. Sustainability 11(23), https://doi.org/10.3390/su11236716

Li, Y.; Li, D.; Bie, S.; Wang, Z.; Zhang, H.; Tang, X.; Zhen, Z. (2018): Numerical simulation for fluid droplet impact on discrete particles with coupled SPH-DEM method. International Journal of Numerical Methods for Heat & Fluid Flow 28(11), pp. 2581–2605, https://doi.org/10.1108/HFF-11-2017-0464

Mayo, L.C.; McCue, S.W.; Moroney, T.J.; Forster, W.A.; Kempthorne, D.M.; Belward, J.A.; Turner, I.W. (2015): Simulating droplet motion on virtual leaf surfaces. Royal Society open science 2(5), p. 140528, https://doi.org/10.1098/rsos.140528

Mukherjee, D.; Zohdi, T.I. (2015): A discrete element based simulation framework to investigate particulate spray deposition processes. Journal of Computational Physics 290, pp. 298–317, https://doi.org/10.1016/j.jcp.2015.02.034

Ni, M.; Wang, H.; Liu, X.; Liao, Y.; Fu, L.; Wu, Q.; Mu, J.; Chen, X.; Li, J. (2021): Design of Variable Spray System for Plant Protection UAV Based on CFD Simulation and Regression Analysis. Sensors (Basel, Switzerland) 21(2), https://doi.org/10.3390/s21020638

Omar, Z.; Qiang, K.Y.; Mohd, S.; Rosly, N. (2016): CFD Simulation of Aerial Crop Spraying. IOP Conference Series: Materials Science and Engineering 160, https://doi.org/10.1088/1757-899X/160/1/012028

Oxford Lasers (2021): VisiSize N60 - Spray Characterisation Tool | Oxford Lasers. https://www.oxfordlasers.com/laser-imaging/visisize-n60, accessed on 21 July 2021

Parra, H.G.; Morales, V.D.A.; Garcia, E.E.G. (2019): Multiphase CFD Simulation of Photogrammetry 3D Model for UAV Crop Spraying. In: New Knowledge in Information Systems and Technologies. Hg. Rocha, Á.; Adeli, H. et al., Cham, Springer International Publishing, pp. 812–822

Pasha, M.; Hare, C.; Ghadiri, M.; Gunadi, A.; Piccione, P.M. (2017): Inter-particle coating variability in a rotary batch seed coater. Chemical Engineering Research and Design 120, pp. 92–101, https://doi.org/10.1016/j.cherd.2017.01.033

Saeedipour, M. (2019): Atomization of two colliding micro liquid jets in a respiratory inhaler: A computational study. In: 29th European Conference on Liquid Atomization and Spray Systems, 2-4.09.2019, Paris

Schmelzle, S.; Asylbekov, E.; Radel, B.; Nirschl, H. (2018): Modelling of partially wet particles in DEM simulations of a solid mixing process. Powder Technology (338), pp. 354–364

Schmidt, M. (1980): Einfluß physikalischer Flüssigkeitseigenschalten auf die Zerstäubung im Pflanzenschutz. Grundlagen der Landtechnik 30(4), S. 126–134, https://440ejournals.uni-hohenheim.de/index.php/Grundlagen/article/view/398

Shen, B.; Ye, Q.; Tiedje, O.; Domnick, J. (2019): Simulation of the primary breakup of non-Newtonian liquids at a high-speed rotary bell atomizer for spray painting processes using a VOF-Lagrangian hybrid model. In: 29th European Conference on Liquid Atomization and Spray Systems, 2-4.09.2019, Paris

Vulgarakis Minov, S. (2015): Integration of imaging techniques for the quantitative characterization of pesticide sprays. Dissertation, Ghent University

Washino, K.; Miyazaki, K.; Tsuji, T.; Tanaka, T. (2016): A new contact liquid dispersion model for discrete particle simulation. Chemical Engineering Research and Design 110, pp. 123–130, https://doi.org/10.1016/j.cherd.2016.02.022

Wu, H.; Xie, X.; Liu, M.; Chen, C.; Liao, H.; Zhang, Y.; Deng, S. (2020): A new approach to simulate coating thickness in cold spray. Surface and Coatings Technology 382, https://doi.org/10.1016/j.surfcoat.2019.125151

Xie, X.; Wang, Y. (2019): Research on Distribution Properties of Coating Film Thickness from Air Spraying Gun-Based on Numerical Simulation. Coatings 9(11), https://doi.org/10.3390/coatings9110721

Yang, F.; Xue, X.; Cai, C.; Sun, Z.; Zhou, Q. (2018): Numerical Simulation and Analysis on Spray Drift Movement of Multirotor Plant Protection Unmanned Aerial Vehicle. Energies 11(9), https://doi.org/10.3390/en11092399

Ye, Q.; Pulli, K. (2017): Numerical and Experimental Investigation on the Spray Coating Process Using a Pneumatic Atomizer: Influences of Operating Conditions and Target Geometries. Coatings 7(1), https://doi.org/10.3390/coatings7010013

Ye, Q.; Shen, B.; Tiedje, O.; Bauernhansl, T.; Domnick, J. (2015): Numerical and Experimental Study of Spray Coating Using Air-Assisted High-Pressure Atomizers. Atomization and Sprays 25(8), pp. 643–656, https://doi.org/10.1615/AtomizSpr.2015010791

Zhang, B.; Tang, Q.; Chen, L.; Zhang, R.; Xu, M. (2018): Numerical simulation of spray drift and deposition from a crop spraying aircraft using a CFD approach. Biosystems Engineering 166, pp. 184–199, https://doi.org/10.1016/j.biosystemseng.2017.11.017

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