This is a repository copy of *Inter-Particle Coating Variability in a Rotary Batch Seed Coater*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/112380/

Version: Accepted Version

Article:

Pasha, M, Hare, C, Ghadiri, M orcid.org/0000-0003-0479-2845 et al. (2 more authors) (2017) Inter-Particle Coating Variability in a Rotary Batch Seed Coater. Chemical Engineering Research and Design, 120. pp. 92-101. ISSN 0263-8762

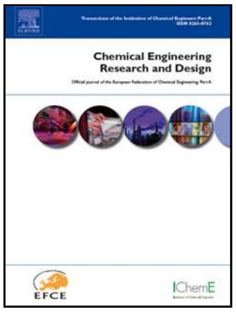
https://doi.org/10.1016/j.cherd.2017.01.033

© 2017 Institution of Chemical Engineers. Published by Elsevier B.V. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/

Reuse
Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/



Title: Inter-Particle Coating Variability in a Rotary Batch Seed Coater

Author: Mehrdad Pasha Colin Hare Mojtaba Ghadiri Alfeno Gunadi Patrick M. Piccione

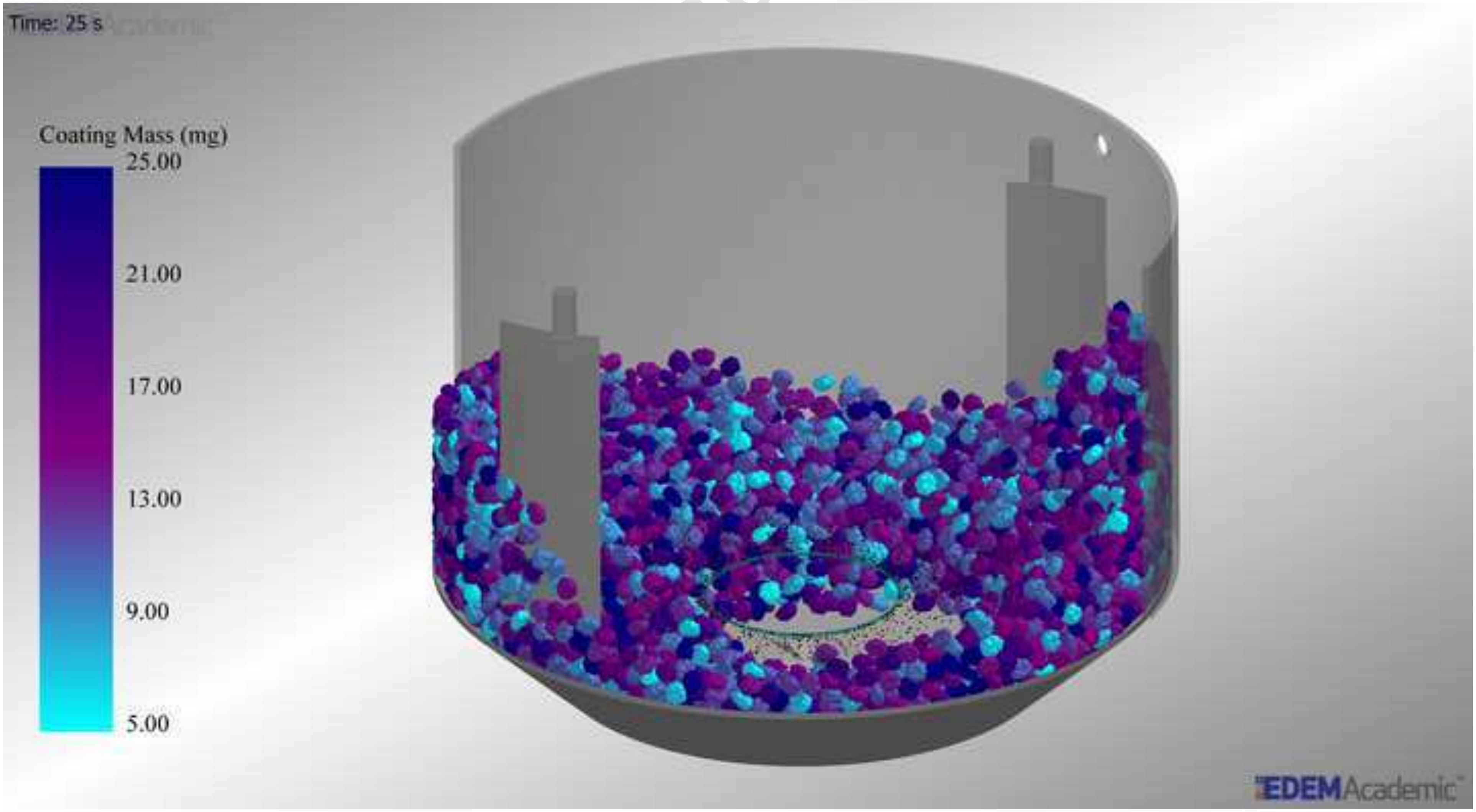
PII: S0263-8762(17)30088-6
DOI: http://dx.doi.org/doi:10.1016/j.cherd.2017.01.033
Reference: CHERD 2565

To appear in:

Received date: 6-7-2016
Revised date: 12-1-2017
Accepted date: 31-1-2017

Please cite this article as: Mehrdad Pasha, Colin Hare, Mojtaba Ghadiri, Alfeno Gunadi, Patrick M. Piccione, Inter-Particle Coating Variability in a Rotary Batch Seed Coater, *<![CDATA[Chemical Engineering Research and Design]]>* (2017), http://dx.doi.org/10.1016/j.cherd.2017.01.033

Graphical Abstract (for review)



- The coating uniformity of corn seeds in a batch seed coater is evaluated by DEM
- Discrete drop coating model is used to evaluate the coating uniformity of the seeds
- Effect of process parameters on coating uniformity of the seeds is investigated
- The atomiser disk position is strongly influencing the coating uniformity
- Optimum process parameters for rotary batch seed coaters are reported

Inter-Particle Coating Variability in a Rotary Batch Seed Coater

Mehrdad Pasha[a], Colin Hare[b], Mojtaba Ghadiri[a,*], Alfeno Gunadi[c], Patrick M. Piccione[d]

[a] *Institute of Particle Science and Engineering, University of Leeds, Leeds, UK*
[b] *Chemical & Process Engineering , University of Surrey, Surrey, UK*
[c] *Process Studies Group, Technology and Engineering, Syngenta Ltd, Jealotts Hill International Research Centre, Bracknell, Berkshire, UK*
[d] *Process Studies Group, Technology and Engineering, Syngenta, Breitenloh 5, Münchwilen, Switzerland*

Abstract

Coating of particulate solids by a thin film layer is of interest in many industrial applications such as seed and tablet coating. In seed processing, seeds are commonly coated with a protective coating layer consisting of fertilisers and disease control agents, such as pesticides and fungicides. Batch coaters are commonly used for this purpose. A typical coater consists of a vertical axis cylindrical vessel with a rotating base and a spray disc in the centre, onto which the coating liquid is fed to atomise and spray-coat the seeds. The seeds are driven around the vessel by its rotating base, and are mixed by two baffles; one on either side of the vessel. In the present study, Distinct Element Method (DEM) simulations are used to model the seed coating process. Corn seed are used as a model

---

[*] Corresponding author.
Email address: `m.ghadiri@leeds.ac.uk` (Mojtaba Ghadiri)

Preprint submitted to Chemical Engineering Research and Design *November 3, 2016*

material and their shape is captured using X-Ray Tomography (XRT), which is approximated in the DEM by clumped spheres. The coating uniformity of the seeds is predicted by implementing a coating model in the DEM, whereby the coating droplets are simulated as very fine spheres projecting tangentially from a ring at the edge of the spinning disk. The size and velocity of droplets leaving the spray disk are measured using high speed video imaging and implemented into DEM simulations. The coating mechanism is represented in the DEM by considering that once a droplet contacts a corn seed, it is removed from the simulation and its mass is attributed to the coating of the corn seed. The distribution of mass of sprayed spheres on the corn seeds and their coefficient of variation are evaluated for a range of process conditions, such as the base rotational speed, atomiser disc position relative to the base and baffle arrangement and designs. It is found that the atomiser disc vertical position, baffle angle and clearance to the wall are most influential, whilst the base rotational speed and baffle width and curvature have only minimal effect.

Keywords:

Coating uniformity, Drum Coater, Particle shape, Coating, Discrete element method, Coating optimisation, Process optimisation

1. Introduction

Coating of particulate solids by a thin film layer is of interest in many industrial applications, such as seed and tablet coating. Particularly in seed coating, seeds are commonly coated with a protective coating layer consisting of fertilisers and pesticides in order to improve their germination. The quality of the finished product is strongly dependent on the effectiveness of the coating liquid formulation and the level of coverage of the coating on the seeds. The latter is influenced by the motion, mixing and coating phenomena of seeds which are directly controlled by process parameters. Hence, understanding the effect of each process parameter on coating uniformity of seeds is essential. To do so, the particle kinematic behaviour (flow field, mixing pattern, etc.) and the residence time of seeds in the coating zone have to be analysed. Discrete Element Method (DEM) [1] provides a robust way of simulating particulate systems and has recently been used to address the coating uniformity of pharmaceutical tablet coating [2, 3, 4, 5]. Inter- and intra particle coating variability are the two parameters for assessing the coating variability. The former is the variation in the average coating mass from a granule to another, whilst the latter is the distribution of coating liquid on the surfaces of individual granules, in which both factors can be quantified using the coefficient of variation [6]. Inter particle coating variability is defined as the coefficient of variation of the coating mass amongst the particles.

In the pharmaceutical industry, horizontal axis drum coaters are commonly used for coating tablets with a thin layer of film. In this type of coater, a large number of tablets are placed inside the drum, which is rotated around its axis. The rotational motion of the drum leads to radial and slight axial mixing of the tablets [7]. The coating film is formed by spraying a liquid onto a moving tablet bed. Mixing and uniformity of coating is enhanced by placing a number of baffles inside the drum. This type of coater however is different to those used for coating seeds with two main differences: i) in seed coating the drum is placed vertically and the motion is brought about by a rotating base; ii) a rotating disc atomiser is used instead of a nozzle sprayer. However, the two types of mixers share the same underlying particle mechanics and knowledge of the former would help understand the latter for which little has been published in the literature. In contrast, the behaviour of particle beds in rotating drums with horizontal axis has been extensively investigated and reported in the literature [7, 8, 9, 10, 11], where it has been found that the drum filling level and Froude number, $Fr \equiv \omega^2 R/g$ (where ω and R are the rotational speed and radius of the drum and g is the gravitational acceleration) influence the particle flow field.

Suzzi *et al.* [12] investigated the effect of tablet shape and fill level on mixing and inter-tablet coating variability in a continuous rotating drum coater for a binary mixture. Considering that mixing promotes good coating, in their study, the mixing efficiency for the all investigated tablet shapes decreased with increasing the fill level of the coater. The dispersive mixing of bi-convex tablets was faster than oval shaped tablets indicating that particle shape should be simulated rigorously. A significantly better performance was achieved at the lowest fill ratio in the case of rounded tablets. In the above work, the inter-tablet coating uniformity was investigated by a first order rate approximation. Moreover, the back-splashing of satellite droplets and the transfer of coating solution from a tablet to neighbouring tablets and walls were neglected. The inter-tablet coating standard deviation was directly correlated to the average fractional residence time of particles in the coating zone, the mass ratio between the droplets retaining and those impinging on the tablet surface, and the rate of droplets arriving on the surface. Based on this approach, Suzzi *et al.* [12] concluded that the average fractional residence time of particles in the coating zone decreased with increasing the fill ratio leading to a decline in coating speed.

Kalbag and Wassgren [6] investigated the inter-tablet coating variability within the spray zone in a horizontal pan coater. They proposed Equation (1) for estimating the coefficient of variation of the tablet coating at a given time (t),

$$CoV(t) = \sqrt{\frac{\Delta t_{seg}}{t}\left(\frac{1}{n/N} - 1\right)} \tag{1}$$

where Δt_{seg} is the time that the tablets stay in the spray zone in a quasi-segregated state, n is the number of tablets being coated per coating trial and N is the total number of tablets in the system. They found that the value of Δt_{seg} depended on the geometry of the pan, tablet shape, spraying mechanism and operational conditions. Consequently, a series of experiments or DEM simulations were required to be carried out to determine the value of Δt_{seg}. The authors reported that the coefficient of variation of tablet residence time followed a power law relation with time. Moreover, Δt_{seg} decreased with increasing the Froude number of the pan, aspect ratio of the spray zone, and frictional coefficients of the particles. This led to a more uniform residence time of tablets being present in the spray zone and consequently coating mass on the tablets.

Li *et al.*[13] investigated the effect of particle size distribution of spherical particles on coating uniformity in an industrial paddle coater using DEM simulations and spray post-processing analysis, known as ray tracing. The coating mass a particle gains during its kth visit to the spray zone was calculated using

$$\Delta m_{Y,k} = R_y A_{tot} \eta_k t_{S,k} \tag{2}$$

where R_y, A_{tot}, η_k and $t_{S,k}$ are the constant spray flux density, unobscured projected surface area, average exposed area percentage and spray zone residence time during the kth visit to the spray zone. Li *et al.* [13] reported that for polydisperse particles, smaller particles tend to have a relatively high frequency of spray zone visits and low shielding by surrounding particles, leading to higher spray preference toward smaller particles in the system. Just *et al.* [14] looked at optimisation of the inter-tablet coating uniformity in a pan coater experimentally, by varying process parameters such as pan load and speed, spray rate, number of spray nozzles and spraying time using a statistical design of experiment approach. A laboratory and a pilot scale pan coaters were used. They reported that a low spray rate and a high pan speed improved the coating uniformity at both scales. The most influential parameter affecting the coating uniformity was found to be the number of nozzles used in the system, where a significant improvement was found by using four spray nozzles as compared to two. They also reported that uniformity of coating was improved by increasing the coating time.

In conclusion, the DEM simulations have proved useful in developing a better understanding of coating operation and optimising it. The methodologies developed for predicting the variation of coating can be extended and applied to corn seed coating. However, no such analysis of coating optimisation has so far been reported for seed coaters in the literature. Hence, in this study the effect of seed coating process parameters on coating uniformity of corn seeds is addressed.

2. Materials and Method

2.1. DEM Simulations

A series of DEM simulations were carried out for a rotary batch seed coater (0.3 m in diameter and 0.21 m in height), as shown in Figure 1, using EDEM$^{\circledR}$ software (DEM-Solutions, Edinburgh, UK) in order to predict the effect of various coating process parameters on the coating uniformity of corn seeds. Atomisation of a liquid stream introduced by a nozzle onto a spraying disc was simulated by generating spheres at a radial position (represented by a ring-shaped virtual geometry) corresponding to the tip of the rotating disc and at a rate conforming to the liquid flow rate. The droplet size and velocity distributions corresponded to the experimental values. On contacting the surfaces of the corn seeds, the droplets were removed and their mass was added to the accumulated coating mass. The base rotates to mobilise the seeds, whilst the vertical plates act as baffles, turning the bed over and ensuring adequate mixing of the seeds in order to increase the uniformity of coating.

A Phoenix Nanotom CT scanner (GE Measurement and Control, US) was used to obtain the 3D image of a single corn seed in the 7.1 - 8.0 mm sieve-cut, as shown in Figure 2a. The shape of corn seeds is then approximated with five clumped sphere (approximately 0.1 % deviation in volume compared to that of the actual seed) with various sizes, as shown in Figure 2b, using ASG2013 software (Cogency, South Africa). It has been shown that this approximation is adequate for predicting the motion of corn seeds in the coater [2]. A bed consisting of approximately 4200 seeds (21,000 spheres), corresponding to 1.4 kg of corn seeds, was used.

2.2. Coating Model

The spray droplets are considered as non-interacting spheres until they contact the corn seeds. Their size and velocity distributions are incorporated in the simulations, based on experimental data obtained by video motion analysis. In the simulations described here, a particle property termed ‘coating liquid mass’ is introduced in addition to the existing properties. The model of Toschkoff *et al.* [15] is used to model the coating process and briefly described here. For contacts between droplets and corn seeds, the droplet mass is added to the property ‘coating liquid mass’ of the corn seed and the droplet is deleted. The momentum of droplets is negligible in comparison to the corn seeds, hence the impact of droplets on the corn seeds would not have a strong influence on the momentum of corn seeds and it is ignored in the force calculations. In addition, inter-droplet collisions were very infrequent in the video recordings and are therefore not considered in the simulations. This significantly improves the calculation speed. However, it is possible to account for these collisions and establish the coalescence phenomenon, but it is beyond the scope of this work. In addition to the above criterion, Hertz-Mindlin contact model with rolling friction based on viscous dissipation [16] is used for simulating inter-particle interactions.

2.3. Implementation of Droplet Generation

In order to incorporate the coating liquid droplets in the DEM simulations, the size and velocity distributions of the droplets are required. There are no data on the size distribution of droplets generated from disc atomisers in the literature. Only the mean or Sauter diameter has been reported [17, 18, 19, 20]. Hence, a series of high speed video recordings were carried out to measure the droplet size and velocity distributions once they were released from the atomiser disc. De-ionised water was used as the spraying liquid, the flow rate of which was fixed at 2.67 ml/s. The motion of droplets was recorded using a Redlake HG-100K high-speed video camera. The camera set up is shown in Figure 3.

The video recording frame rates for droplet size analysis and velocity measurement are different to ensure best condition for each case. For the former, the frame rate was 200 fps. The size of each droplet at each video frame was measured every 5 ms using ImageJ software, based on the number of pixels. This process was carried out over a period of 10 s. The droplets smaller than 50 µm in diameter were excluded from the analysis as they were very infrequent. Moreover, due to the resolution of captured images, they did not contain an adequate number of pixels (i.e. less than 5 pixels in diameter). For the droplet velocity measurement, the frame rate was 2,000 fps. The magnitude of droplet velocity was calculated from the travelled distance of each droplet between the consecutive video frames with a time difference of 500 µs. The droplet size and velocity distributions are shown in Figures 4 and 5, respectively. The measured droplet size distribution here agrees with the mean droplet size and Sauter diameter correlations reported in the literature [17]. However, the correlations in the literature do not provide any information about the size distribution.

For accurate representation of the droplets in the DEM simulations, it is important to take into account the directional motion of the droplets once they are released from the atomiser disc. Hence, from high-speed video recordings it was found that the droplets moved tangentially relative to the edge of the atomiser, as indicated by the tracked position of some of the droplets after being released from the atomiser disc in Figure 6.

Based on the measured droplet size and velocity distributions and the direction of their movement, a custom code was implemented in EDEM software for generation and movement of droplets. A ring-shaped virtual geometry with 1.5 mm height and a small thickness of 0.75 mm with the outer diameter corresponding to the disc atomiser diameter was considered as the particle factory for generation of the droplets. The droplets were randomly generated inside the particle factory and at the first time step of generation of each droplet, they were given an initial acceleration, which led to the desired tangential velocity at the end of the subsequent time step. The schematic diagram of how the droplets are generated in the model is shown in Figure 7. In the simulations, the rate of generation of droplet spheres was chosen such that their volumetric flow rate was equal to that used in the experiments, i.e. 2.67 ml/s. This produced about 36,300 spheres per second. The droplets were generated after 1 s of real time operation where the motion of seeds had reached steady state.

The elastic modulus of seeds was reduced by two orders of magnitude, compared to the experimental measurements, in order to speed up the simulations. This was considered to be safe since the motion of non-adhesive particles was of interest. It has been shown that varying elastic modulus to this degree is not influential on the motion of such particles in DEM simulations [21, 22]. Coefficients of restitution and sliding friction of particles were measured experimentally using a high-speed video camera and the NanoCrusher (Micro Materials, UK), respectively. The particle and simulation properties are summarised in Tables 1 and 2, where particle size follows a normal distribution. The uniformity of corn seeds coating is simulated by varying the baffle angle, distance to the wall and geometry, spraying disc position and rotational speed of the base of the coater.

3. Results and Discussion

3.1. Baffle Angle and Wall Clearance

The effect of baffle angle and clearance to the walls on the coating uniformity of corn seeds are investigated by varying from 25° to 55° and 5 mm to 20 mm, respectively. The latter was considered such that it represented a clearance corresponding to approximately 1 to 4 corn seed diameters. The definitions of the angle, α, and clearance, d, are shown in Figure 8.

For all the investigated cases, the rotational speed of the coater base, atomiser disc distance to the base and flow rate of coating droplets were kept constant at 300 rpm, 30 mm and 2.67 ml/s, respectively. The coating simulations were carried out for 25 s of real time operation using the flat baffle design, as shown in Figure 9. The evolution of coating variability with time is shown Figure 10. For 25 s of coating time, which is typically used for industrial scale coaters, the CV of coating mass has decreased considerably approaching a relative asymptotic level.

The effect of baffle clearance to the wall on coating uniformity of corn seeds is shown in Figure 11. For all investigated cases, the coating mass variability is reduced as the clearance gap is increased to 15 mm, after which it increases again.

Therefore, the optimum baffle clearance is around 15 mm for the investigated system here for all the baffle angles. This clearance represents approximately two to three particle diameters. The difference between the two extreme cases of clearance gap (5 and 20 mm) investigated is considered significant, where 5 % improvement in terms of coating uniformity is achieved. The effect of baffle angle on coating variability is shown in Figure 12. For clearance of 10 to 20 mm, the coating uniformity is improved by increasing the baffle angle to 35 – 45°, beyond which the CV is slightly increased. However, in the case of a 5 mm clearance, the optimum baffle angle was found to be 25°.

Using the above analysis, it can be concluded that optimum values of baffle angle and clearance to the wall of the coater are 45° and 15 mm, respectively, where the coating uniformity of corn seeds can be improved by 7% between the two extremes of coating mass CV. The clearance gap controls the fraction of the surface that is renewed after each circulation of base, since this parameter controls the thickness of the particle layer being sliced off from the bed surface. Moreover, the baffle angle controls the direction and the position of the particles being sliced from the bed. In combination, these two parameters control the surface renewal rate of the bed, which directly influences the coating uniformity of corn seeds since only the particles at the surface receive coating liquid. This process is amenable to analysis by the surface renewal theory, similar to work of Mann [23] and Freireich and Li [24].

3.2. Baffle Geometry

In addition to baffle angle and clearance, surface renewal rate and motion of particles after being sliced off from the surface depend on the baffle shape. Hence a number of baffle designs were proposed to investigate the influence of baffle shape. For this purpose, two key features of the shape were considered: width and geometry. For the curvature of the baffle, two cases were considered: flat and curved faces; and three baffle widths were considered for each, as shown in Figure 9. In order to compare the results, all other simulation parameters such as position of atomiser disk (30 mm), base rotation speed (300 rpm) and total mass input (1.4 kg) were kept constant and the optimum baffle angle (45 °) and clearance gap (15 mm) were used.

The coating mass CV values for the proposed baffle designs are shown in Figure 13. It is clear that the effect of baffle width on coating uniformity of corn seeds for all the investigated cases is not significant, as CV increases by about 1% only when the baffle width is doubled from 30 to 60 mm for the flat baffles. However, in the case of the curved baffles, a baffle width of 45 mm improves inter-particle coating uniformity by approximately 1 – 2% compared to widths of 30 and 60 mm, respectively. Comparing the flatness and curvature of the baffles, the curvature of the baffle does not strongly influence the coating uniformity; however, the curved baffle with a width of 45 mm results in a slightly lower coefficient of variation than the original flat baffle.

By fixing the baffles clearance and angle, regardless of the width and curvature of the baffles, the fraction of particles being sliced off from the surface of the bed is more or less similar. The baffle curvature and width are expected to affect the motion of particles after passing the baffles, rather than influencing the surface renewal rate.

3.3. Atomiser Vertical Position

Since the coating droplets are generated using a rotating disc atomiser rather than a sprayer, a thin layer of droplets are generated. The position of the atomiser disc relative to the base of the coater affects the fraction of seeds being coated on the surface of bed. A series of DEM simulations were carried out by varying the vertical position of atomiser disc relative to the base of the coater from 30 to 70 mm, using the flat design baffle (30 mm wide) with clearance and angle of 15 mm and 45, respectively. The particle coating mass CV values using the proposed vertical positions of the atomiser disc are shown in Figure 14. The coating uniformity of the particles improves as the vertical position is increased to 50 mm from the base; however beyond this point it starts to deteriorate (CV increases). Comparing the optimised vertical position of the spray disc (50 mm) with the initial position used in the earlier simulations (30 mm), the position of the disc relative to the base of coater has a notable influence on the coating variability and approximately 5% improvement of coating variability is achieved as shown in Figure 14. Hence, it can be concluded that this process parameter is one of the key influential parameters in the coating process using this type of coater.

3.4. Base Rotation Speed

In addition to the dynamics of droplet generation and surface renewal rate, the number of coating events (number of bed turnovers) is expected to influence the coating variability of the particles in the process. In general, a larger number of rotations should lead to a higher probability of new and less coated particles being available for coating at the surface of the bed, thus leading to a higher probability that the particles will be more uniformly coated in the system. It is expected that a minimum number of bed turnovers is required to let all the particles become coated. However, an excessively high rotational speed would lead to higher impact velocities of the seeds to the baffles, which may damage both the particles and their coating. In this study, the intention was to focus on the coating variability of particles rather than any damage on their coating; hence the potential damage to the coating of the seeds is disregarded. Therefore only three base rotational speeds of 300, 400 and 500 rpm were used to investigate their effect on the coating variability. It was found that increasing the speed improved the coating uniformity of the corn seeds but only very slightly, as approximately 1.4 % improvement was achieved.

4. Conclusions

The effect of various seed coater process parameters on coating variability of corn seeds in a batch seed coater was investigated using DEM simulations. In the coating model, the coating liquid droplets were represented by small spheres and once brought into contact with a corn seed surface, their mass was stored in the corn seeds coating mass parameter, and they were removed from the simulation. The uniformity of coating was then analysed based on coefficient of variation coating mass of the seeds. It was shown that using this model the amount of the coating on each particle could be tracked; hence useful information such as distribution of coating mass among the particles and coefficient of variation of coating mass of the particles could be assessed. Among the proposed process parameters, it was found that the position of the atomiser disc relative to the base of coater and baffles clearance to the walls strongly influence the coating uniformity of the particles. Moreover, It is found that the position of atomiser disc plays an important role on improving the coating uniformity of particles and a change in distance from the base of the coater, from 30 to 50 mm, decreases the particle coating mass CV by 5%. In the case of baffle clearance to the wall, using the flat baffle design, a clearance to the wall of 15 mm provides the lowest inter-particle coating variability compared to small and large clearance gaps. An improvement of approximately 7% is achieved between the best and worst case combination of baffle angle and clearance gap investigated in this study. On the other hand, other process parameters (e.g. baffles angle, curvature, width and base rotational speed) had insignificant effects on coating uniformity of the particles where only a 1 to 2% change in coating mass coefficient of variation is observed.

5. Acknowledgements

The financial support of Syngenta through its Technology & Engineering's Strategic & Enabling Technology programme is gratefully acknowledged. The authors would like to thank Dr Neil George, Syngenta Ltd, UK for his support and encouragement, and Phil Taylor of Syngenta Jealott's Hill Formulation Technology Group for providing the seed coater. The authors also would like to thank DEM Solutions (Edinburgh, UK) for their technical support and providing additional software licences for this work.

References

[1] P. A. Cundall, O. Strack, A discrete numerical model for granular assemblies, Gotechnique 29 (2) (1979) 47–65. `doi:10.1680/geot.1979.29.1.47`.

[2] M. Pasha, C. Hare, M. Ghadiri, A. Gunadi, P. M. Piccione, Effect of particle shape on flow in discrete element method simulation of a rotary batch seed coater, Powder Technology 296 (2016) 29 – 36. `doi:doi:10.1016/j.powtec.2015.10.055`.

[3] P. Cleary, Dem prediction of industrial and geophysical particle flows, Particuology 8 (2) (2010) 106–118. `doi:10.1016/j.partic.2009.05.006`.

[4] H. Zhu, Z. Zhou, R. Yang, A. B. Yu, Discrete particle simulation of particulate systems: A review of major applications and findings, Chemical Engineering Science 63 (23) (2008) 5728–5770. `doi:10.1016/j.ces.2008.08.006`.

[5] C. Hare, U. Zafar, M. Ghadiri, T. Freeman, M. J. Murtagh, Analysis of the dynamics of the FT4 powder rheometer, Powder Technology 285 (2015) 123–127. `doi:doi:10.1016/j.powtec.2015.04.039`.

[6] A. Kalbag, C. R. Wassgren, Inter-tablet coating variability: Tablet residence time variability, Chemical Engineering Science 64 (11) (2009) 2705–2717. `doi:10.1016/j.ces.2009.02.037`.

[7] A. Muliadi, P. Sojka, A review of pharmaceutical tablet spray coating, Atomization and Sprays 20 (7) (2010) 611–638. `doi:10.1615/AtomizSpr.v20.i7.40`.

[8] K. Yamane, T. Sato, T. Tanaka, Y. Tsuji, Computer simulation of tablet motion in coating drum, Pharmaceutical Research 12 (9) (1995) 1264–1268. `doi:10.1023/A:1016201102355`.

[9] T. Leaver, H. Shannon, R. Rowe, A photometric analysis of tablet movement in a side-vented perforated drum (accela-cota), Journal of Pharmacy

and Pharmacology 37 (1) (1985) 17–21. `doi:10.1111/j.2042-7158.1985.tb04924.x`.

[10] J. Park, C. R. Wassgren, Modeling the dynamics of fabric in a rotating horizontal drum using the discrete element method, Particulate Science and Technology 21 (2) (2003) 157–175. `doi:10.1080/02726350307491`.

[11] S. Sandadi, P. Pandey, R. Turton, In situ, near real-time acquisition of particle motion in rotating pan coating equipment using imaging techniques, Chemical Engineering Science 59 (24) (2004) 5807–5817. `doi:10.1016/j.ces.2004.06.036`.

[12] D. Suzzi, G. Toschkoff, S. Radl, D. Machold, S. D. Fraser, B. J. Glasser, J. G. Khinast, Dem simulation of continuous tablet coating: Effects of tablet shape and fill level on inter-tablet coating variability, Chemical Engineering Science 69 (1) (2012) 107–121. `doi:10.1016/j.ces.2011.10.009`.

[13] J. Li, C. Wassgren, J. D. Lister, Multi-scale modeling of a spray coating process in a paddle mixer/coater: The effect of particle size distribution on particle segregation and coating uniformity, Chemical Engineering Science 95 (2013) 203–210. `doi:10.1016/j.ces.2013.03.014`.

[14] S. Just, G. Toschkoff, A. Funke, D. Djuric, G. Scharrer, J. Khinast,

K. Knop, P. Kleinebudde, Optimization of the inter-tablet coating uniformity for an active coating process at lab and pilot scale., International journal of pharmaceutics 457 (1) (2013) 1–8. `doi:10.1016/j.ijpharm.2013.09.010`.

[15] G. Toschkoff, S. Just, A. Funke, D. Djuric, K. Knop, P. Kleinbudde, G. Scharrer, J. G. Khinast, Spray models for discrete element simulations of particle coating processes, Chemical Engineering Science 101 (2013) 603–614. `doi:10.1016/j.ces.2013.06.051`.

[16] Y. Zhou, B. Wright, R. Yang, B. Xu, A. Yu, Rolling friction in the dynamic simulation of sandpile formation, Physica A: Statistical Mechanics and its Applications 269 (24) (1999) 536 – 553. `doi:10.1016/S0378-4371(99)00183-1`.

[17] W. H. Walton, W. C. Prewett, The production of sprays and mists of uniform drop size by means of spinning disc type sprayers, Proceedings of the Physical Society. Section B 62 (6) (1949) 341. `doi:10.1088/0370-1301/62/6/301`.

[18] R. P. Fraser, P. Eisenklam, Liquid atomization and the drop size of sprays,

Transactions of the Institution of Chemical Engineers 34 (4) (1956) 294–319.

[19] D. J. Ryley, Analysis of a polydisperse aqueous spray from a high-speed spinning disk atomizer, British Journal of Applied Physics 10 (4) (1959) 180.

[20] L. M. Boize, N. Dombrowski, The atomization characteristics of a spinning disc ultra-low volume applicator, Journal of Agricultural Engineering Research 21 (1) (1976) 87 – 99. `doi:10.1016/0021-8634(76)90101-3`.

[21] S. Lommen, D. Schott, G. Lodewijks, {DEM} speedup: Stiffness effects on behavior of bulk material, Particuology 12 (2014) 107 – 112. `doi:10.1016/j.partic.2013.03.006`.

[22] R. Moreno-Atanasio, B. Xu, M. Ghadiri, Computer simulation of the effect of contact stiffness and adhesion on the fluidization behaviour of powders, Chemical Engineering Science 62 (12) (2007) 184 – 194. `doi:10.1016/j.ces.2006.08.036`.

[23] U. Mann, Analysis of spouted-bed coating and granulation. 1. batch operation, Industrial & Engineering Chemistry Process Design and Development 22 (2) (1983) 288–292. `doi:10.1021/i200021a019`.

[24] B. Freireich, J. Li, A renewal theory approach to understanding interparticle coating variability, Powder Technology 249 (2013) 330 – 338. `doi:http://dx.doi.org/10.1016/j.powtec.2013.08.040`.

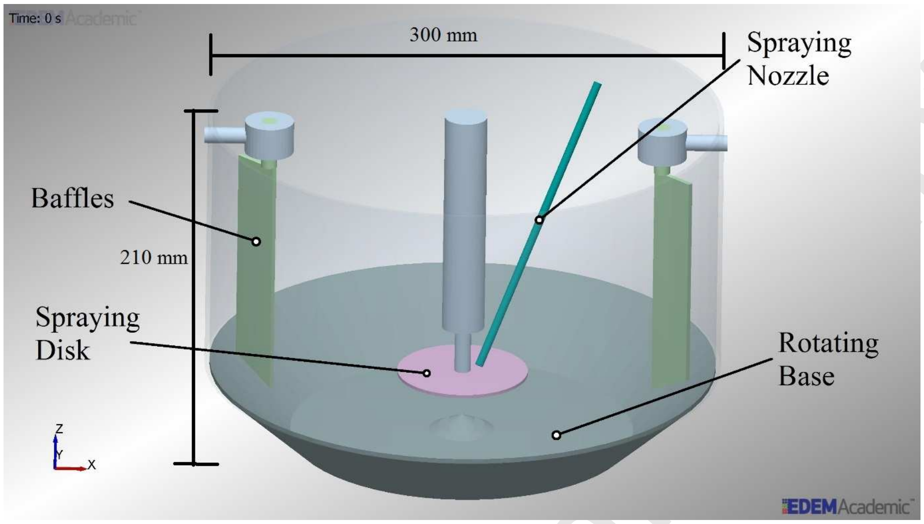


Figure 1: Geometry of vertical batch seed coater.

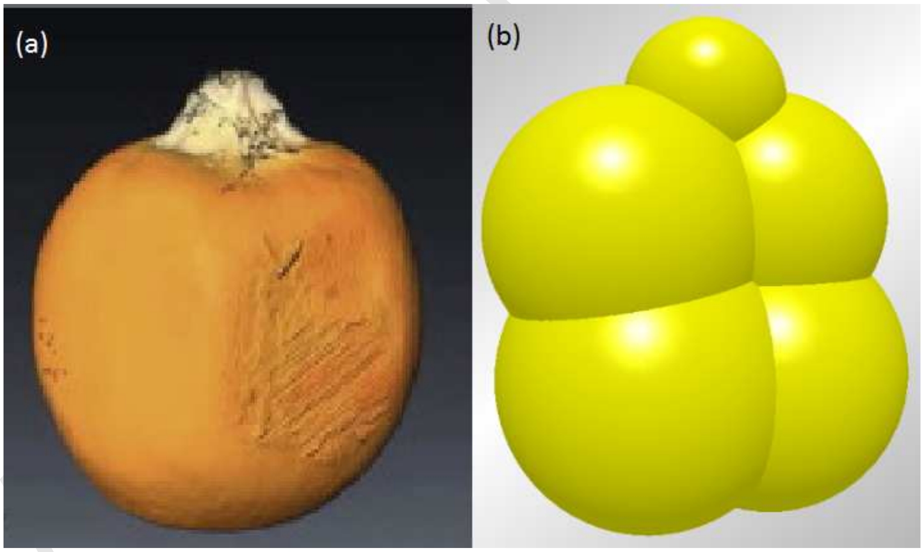


Figure 2: (a) 3D captured shape of corn seed using XRT and (b) representation of corn seed shape by five overlapped spheres in DEM simulation.

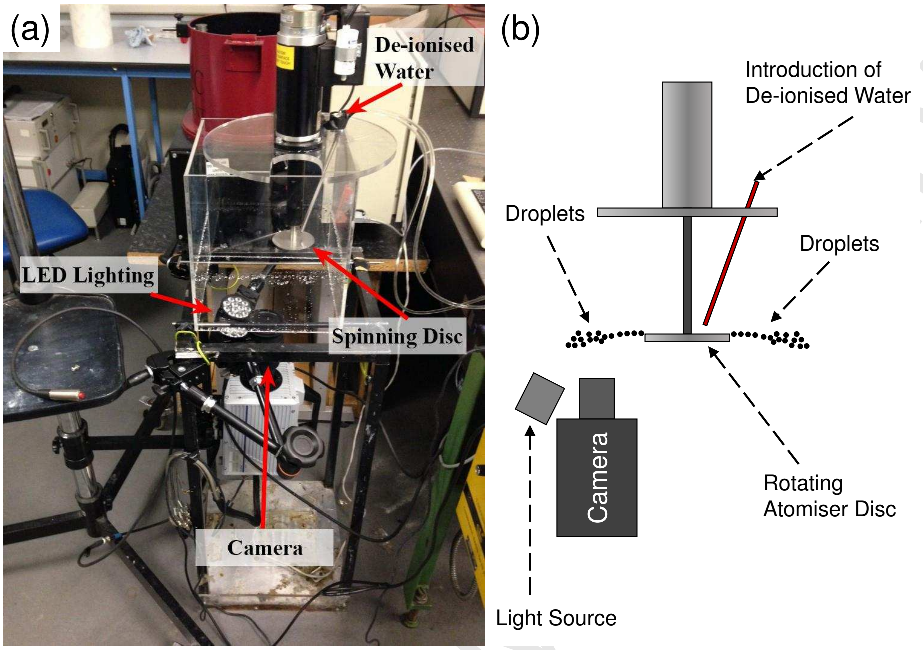


Figure 3: High-speed camera set-up for measuring droplets size and velocity distributions; a) real image and b) schematic image of the set-up.

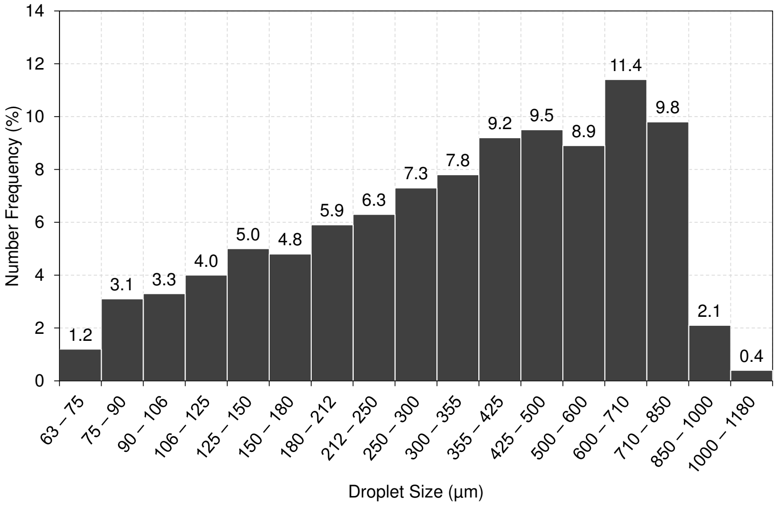


Figure 4: Measured de-ionised water droplet size distribution using high-speed video imaging.

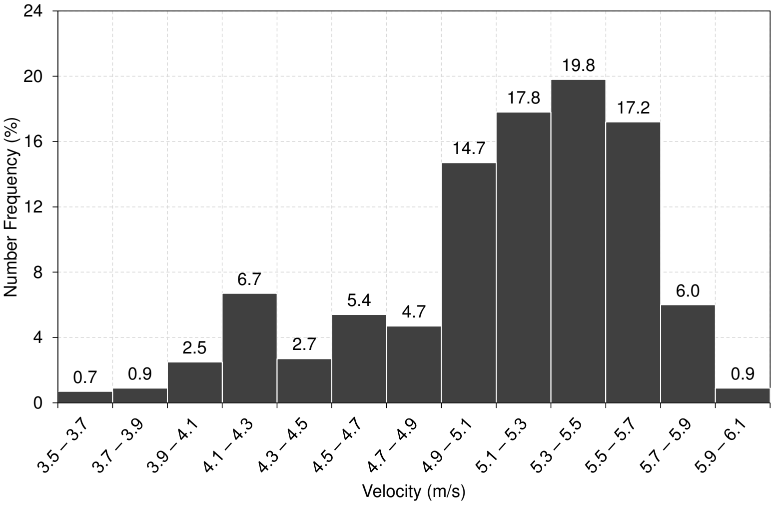


Figure 5: Measured de-ionised water droplet velocity distribution using high-speed video imaging.

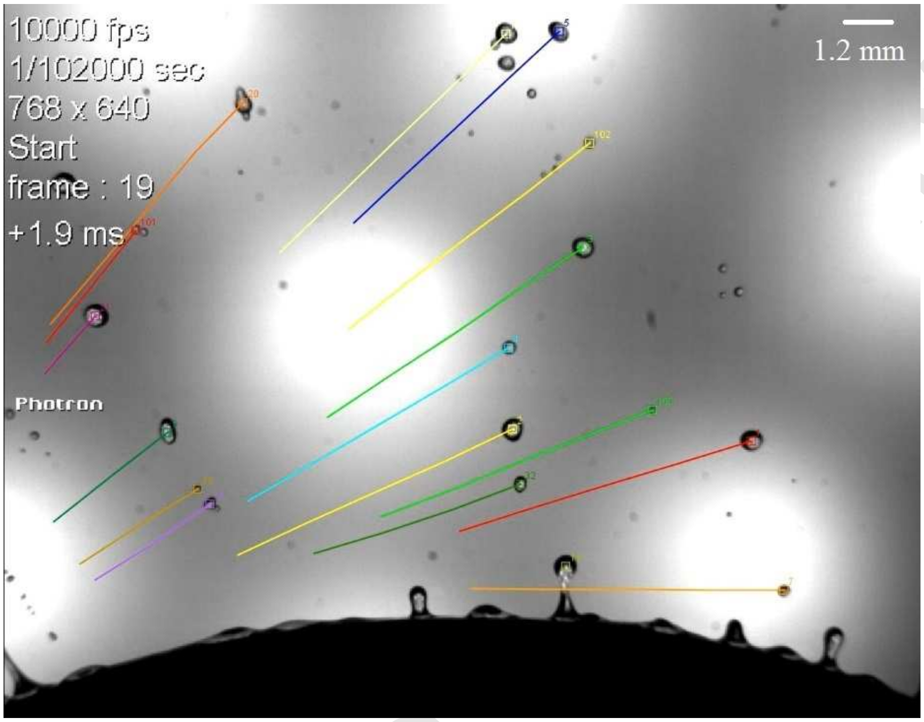


Figure 6: Motion of de-ionised water droplets after being released from the atomiser disc. The coloured lines are showing the tracked position of the droplets in the high-speed video images.

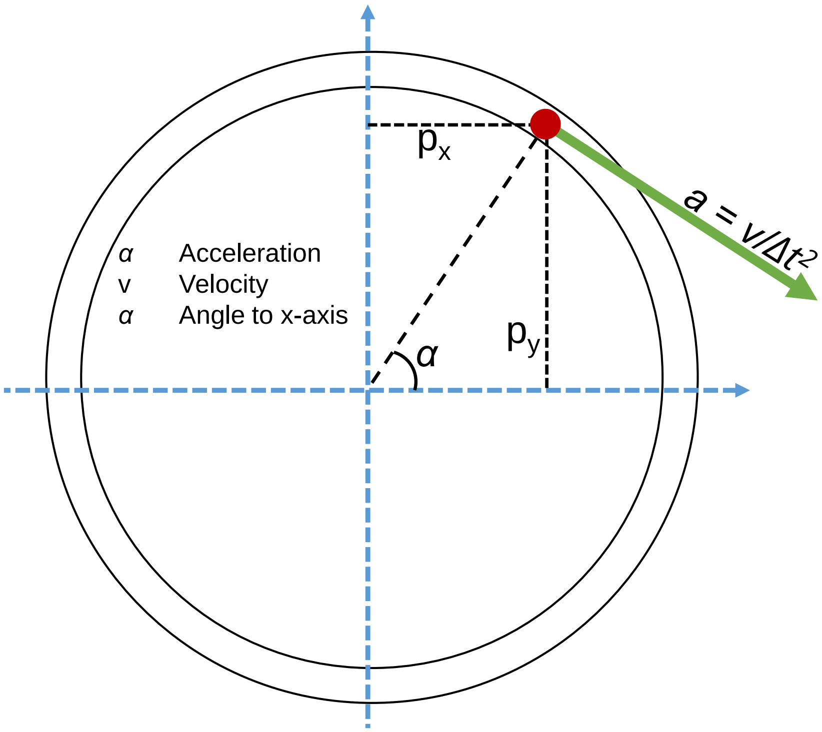


Figure 7: Schematic representation of generation and movement of droplets being released from the atomiser disc in DEM simulations, where p_x and p_y are X and Y position of the droplets relative to the centre point of the ring.

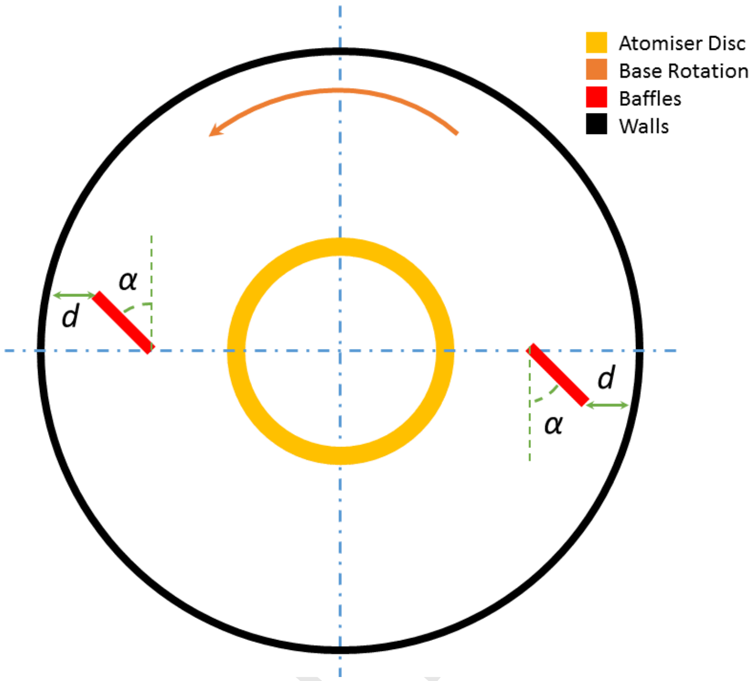


Figure 8: Schematic representation of baffle angle, α, and clearance gap to the walls, d, in the DEM simulations.

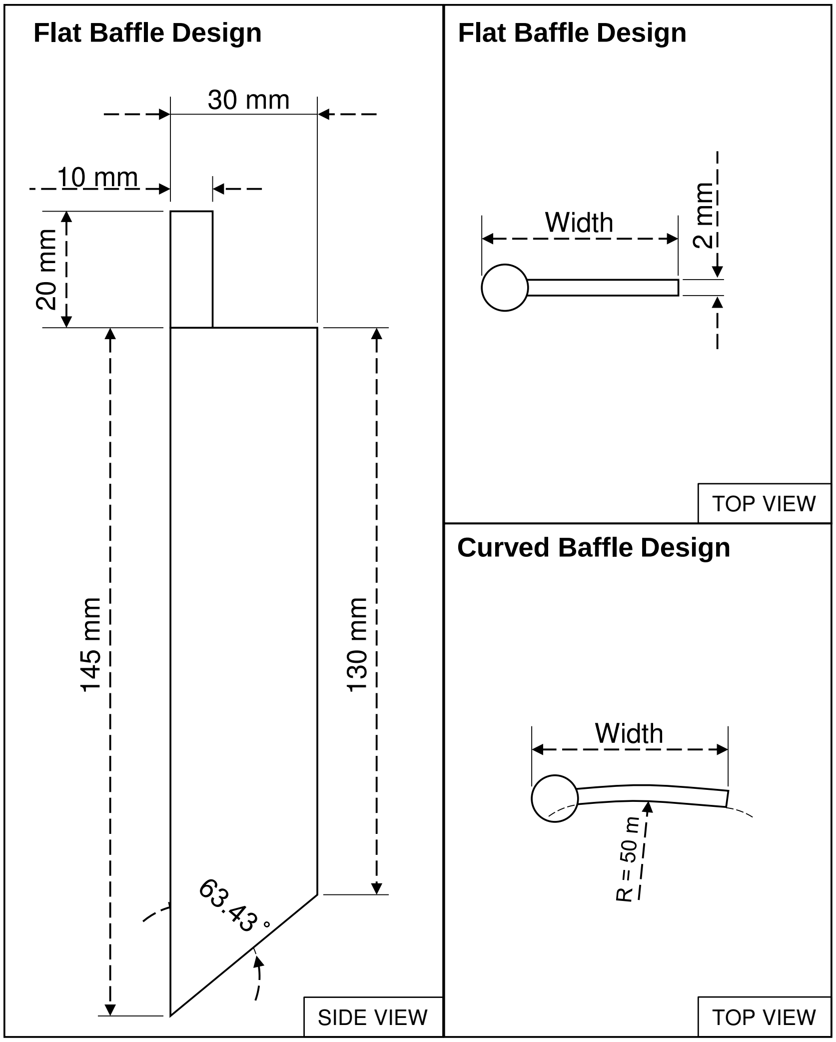


Figure 9: Schematic design of the baffles used in this study. The left schematic represents the original baffle design and the right two schematics represent the changes which has been made to investigate the effect of baffle geometry on coating uniformity.

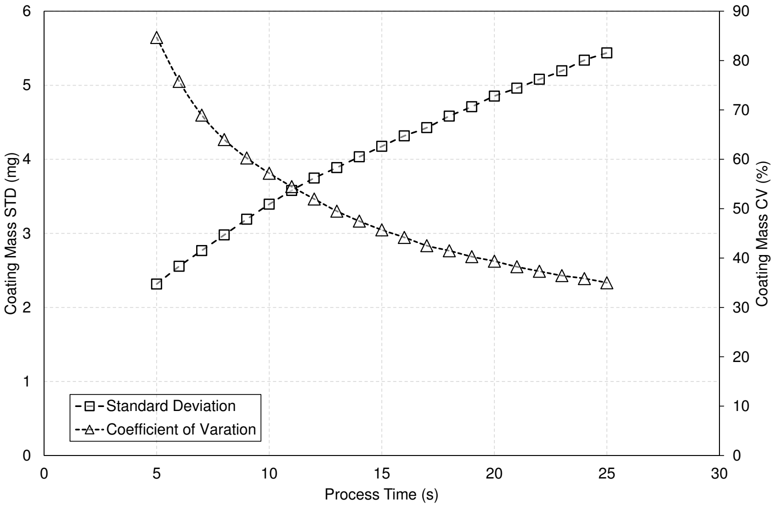


Figure 10: Standard deviation and CV of coating mass of corn seeds as a function of coating time for baffle angle and clearance gap of 45° and 15 mm, respectively.

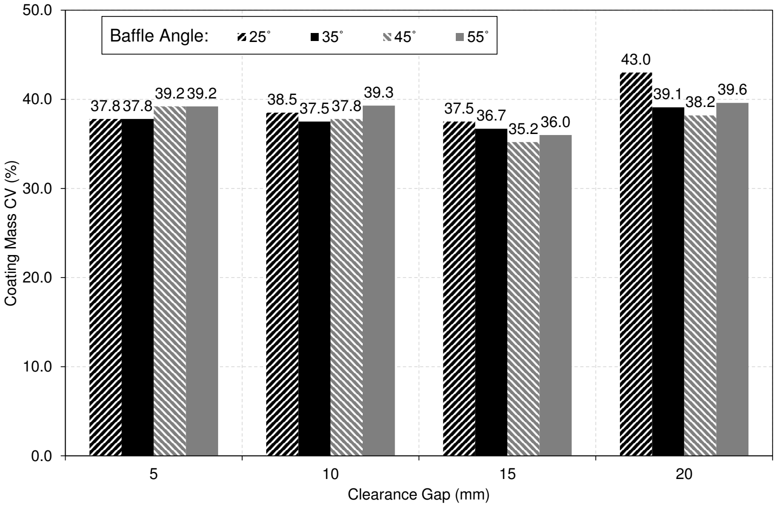


Figure 11: Effect of baffles clearance gap to the wall on coating uniformity of corn seeds in DEM simulations.

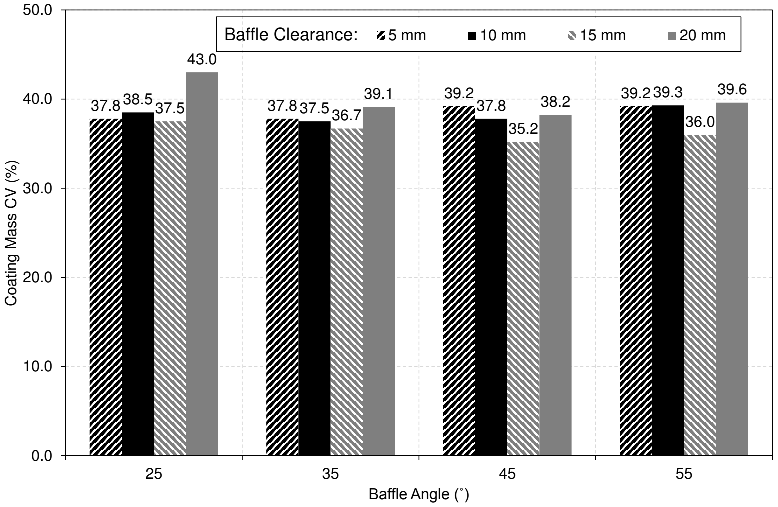


Figure 12: Effect of baffles angle on coating uniformity of corn seeds in DEM simulations.

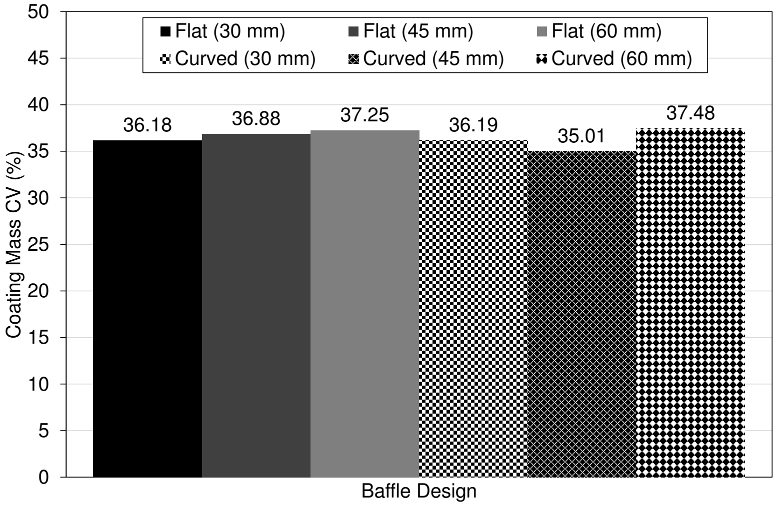


Figure 13: Effect of flatness and curvature of the baffles on coating uniformity of corn seeds in DEM simulations.

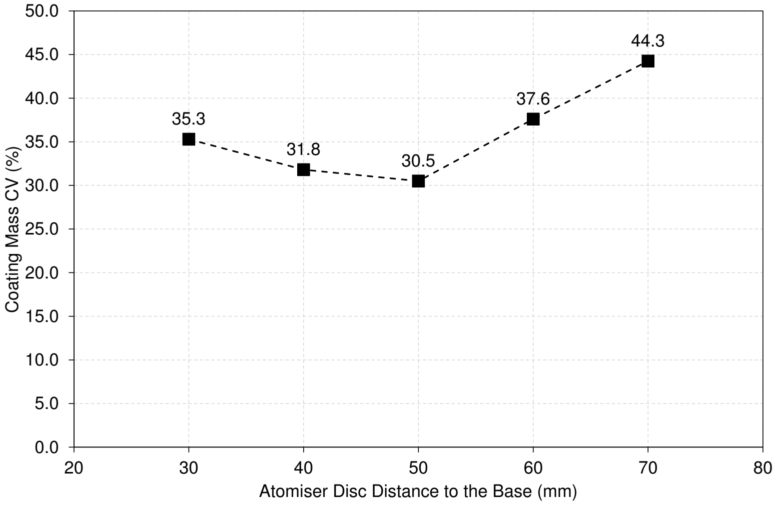


Figure 14: Effect of vertical position of atomiser disc relative to the base of coater on coating uniformity of corn seeds in DEM simulations.

Table 1: Properties of particles and walls used in DEM simulations.

Property	Seeds	Walls
Particle diameter (mm)	7.5 ± 3%	–
Shear modulus (GPa)	0.01	70
Density (kg/m^3)	1163	7800
Poisson's ratio (–)	0.25	0.3

Table 2: Particle interaction properties used in DEM simulations.

Property	Seed – Seed	Seed – Wall
Coefficient of sliding friction (–)	0.3	0.3
Coefficient of rolling friction (–)	0.01	0.01
Coefficient of restitution (–)	0.6	0.69