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Modeling Weight Variability in a Pan Coating Process Using Monte Carlo Simulations

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ABSTRACT

The primary objective of the current study was to investigate process variables affecting weight gain mass coating variability (CV_m) in pan coating devices using novel video-imaging techniques and Monte Carlo simulations. Experimental information such as the tablet location, circulation time distribution, velocity distribution, projected surface area, and spray dynamics was the main input to the simulations. The data on the dynamics of tablet movement were obtained using novel video-imaging methods. The effects of pan speed, pan loading, tablet size, coating time, spray flux distribution, and spray area and shape were investigated. CV_m was found to be inversely proportional to the square root of coating time. The spray shape was not found to affect the CV_m of the process significantly, but an increase in the spray area led to lower CV_ms. Coating experiments were conducted to verify the predictions from the Monte Carlo simulations, and the trends predicted from the model were in good agreement. It was observed that the Monte Carlo simulations underpredicted CV_ms in comparison to the experiments. The model developed can provide a basis for adjustments in process parameters required during scale-up operations and can be useful in predicting the process changes that are needed to achieve the same CV_m when a variable is altered.

KEYWORDS: Pan coating, video imaging, mass coating variability, Monte Carlo, spray shape.

INTRODUCTION

With the advent of process analytical technology (PAT), a new US Food and Drug Administration initiative, the industry is focusing on improving manufacturing efficiency and product quality.[1] The goal of PAT is to adopt innovative technologies to improve product quality without validation risks and production delays. One of the key components of this knowledge-based approach is developing a better understanding of manufacturing processes. With this in mind, the current study focuses on understanding a key unit operation in the pharmaceutical industry, namely pan coating. With the experimental and modeling approaches introduced in this study, the effects of variables used in the pan coating process can be quantified on a sound scientific basis and a rational method for process improvement can be formulated.[2] The variability of coating weight gain between tablets is of significant interest to the pharmaceutical industry, especially when an active or functional coating is applied to the tablets. For relatively large tablets (diameter > 6.35 mm), such coatings are typically performed in pan coating devices. To improve coating performance, it is essential to understand the movement of particles inside a pan coater and the factors that control it. These factors include the movement of tablets within the moving bed, the frequency and distribution of tablet appearances in the spray zone, and the projected surface area of tablets that "see" the spray. These factors in turn are dependent on the operating conditions (eg, drum speed, drum solids loading, the presence/absence of baffles).[1-3]

The movement of tablets inside a rotating drum has been studied by using different experimental techniques (eg, particle tracking techniques such as video imaging, positron emission particle tracking, near-infrared spectroscopy, particle imaging velocimetry, and magnetic resonance imaging) discussed in more detail by Pandey and Turton.[3] These techniques capture the dynamics of tablet movement effectively, but most of them do not account for the spray dynamics of the system and hence provide only limited information from a coating perspective.

The modeling work in this area has not been extensive. Modeling of a pan coating system can be done in several ways and at different levels.[4] The different approaches include theoretical models such as the continuum model proposed by Khakhar et al (1997),[5] renewal theory models (Mann),[6] population balance models (Denis et al),[7] discrete element modeling (DEM),[8,9] and Monte Carlo simulations. A more detailed discussion of these different approaches is provided by Pandey et al.[1] The theoretical models help to describe the movement of particles inside the rotating drum and can be useful for mixing studies. However, they do not address the spray dynamics of a pan coating system. DEM

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approaches have the same problem. In addition, DEM is time-intensive, as Newton's equations of motion are solved for each particle at every time step. This becomes extremely time-consuming for a pan coating system where the number of particles in the system is high. The advantages of these techniques are that no experimental work is required, although one can argue that the techniques may not offer a true representation of the coating process. On the other hand, Monte Carlo simulations capture experimental information and allow prediction of coating mass variability at the conditions of the experiments.

In general, the Monte Carlo method incorporates theoretical models and experimental data to predict parameters of interest in a coating/mixing operation. The Monte Carlo method has been previously used to simulate dispersion or axial mixing in rotating drums.[10-13] It can be thought of as a quantitative exercise done by randomly sampling from the parameter probability distributions to predict the outcome expected from theory or experiments. It is assumed that the average of all outcomes of the randomly sampled probability distributions yields an accurate estimate of the outcome of the real process. Rogers and Gardner[14] extended a simple physical dispersion model with a Monte Carlo method to simulate particulate transport and dispersion for powder flow in a horizontal rotating cylinder. Good agreement was found in the dispersion coefficient values (0.00641-0.0151 cm^2/s) between experimental and simulation results for different fractional fill levels and mixing times. Black[15] predicted dispersion in a similar system using probability distributions for movement in the radial direction by tracking a single particle in batch rotating drums. The model was similar to the one developed by Rogers and Gardner.[14] Kohav et al[16] proposed different variations of models similar to Black's. These models vary in the way the randomness of the radial position is treated. Both the models predicted much less dispersion than that observed in experiments. They neglected the contribution of particle collisions on the bed surface. Cahn and Fuerstenau[10] used Monte Carlo simulations to model axial dispersion of particles moving in a plane perpendicular to the axis of the drum. They studied the effects of drum speeds and fill combinations on the rotational speed and probability distributions of number of particles leaving sections of the bed surface per bed revolution, particle movement direction, and extent of axial movement. It was concluded that a given particle was more likely to leave a section and more likely to travel a greater distance as the speed and fill were increased, but data for the average bed rotation and the distributions were not published.

Although extensive work has been done on coating, transport, dispersion, and agglomeration/granulation of particles using Monte Carlo simulations in fluidized beds,[11,12] no attempts have been made to relate the probability distributions of the events in a pan coater with parameters such as rotational speed, volumetric fill, drum diameter, and particle properties, and hence this was the focus of the current work. The primary objective of this study was to investigate process variables affecting weight gain mass coating variability (CV_m) in pan coating devices using Monte Carlo simulations and video-imaging techniques.[17]

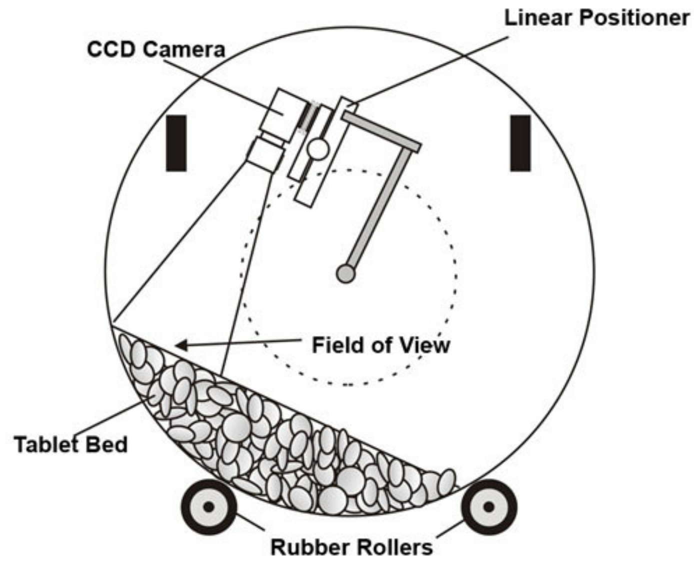

Figure 1. Experimental setup of the pan coater with the video-imaging system.

Materials and Methods

Experimental Setup

The pan used in this work, which was built in-house, consisted of 2 transparent Plexiglass discs, each 57.5 cm in diameter, separated by a 10-cm perforated aluminum strip, as shown in Figure 1. There were 8 slip bars and no baffles in the pan. A flexible fiber-optic light guide that fit onto the end of the lens provided illumination inside the pan. A linear positioner was used to point the camera at the desired position relative to the tablet bed. The camera was mounted inside the rotating drum in approximately the same place and position that a spray gun would be found in a regular pan coater and was adjusted to scan an area covering what would be the normal spray zone during a coating operation. This camera took images at a framing rate of 25 Hz and was connected to a digital frame grabber board (Micro Disc, Yardley, PA). The experimental setup is more fully discussed in Pandey and Turton.[3]

The tablets inside the pan were first coated with 4% black Opadry (Colorcon, West Point, PA) and then with 0.25% clear Opadry. An identical white tracer tablet was coated with 4.25% clear Opadry and introduced into the bed of black coated tablets. The movement of this tracer tablet was recorded by the charged couple device camera. The particles used for this work were standard round placebo tablets (6.3 mm, 7.9 mm, and 10.4 mm). The coated tablets used were placebo units supplied by Mylan Pharmaceuticals (Morgantown, WV). Based on the *Tableting Specification Manual* (APhA Publications, 2005) the allowable tolerance for the diameter of round tooling was 0.0000 inches to –0.0005 inches.

This video-imaging technique enables in situ study of particle motion as the tablets pass under the spray gun; in most other studies, video imaging has been conducted from outside the side wall of the pan. Another major advantage of this technique is that full frames of image data need not be stored for postprocessing, and a 30-minute experiment typically generates a small data file (less than 1 Mb). This technique provides a scientific approach to evaluating CV_m as opposed to the case study approach that is typically used. The data generated were used as input for a mechanistic model to predict CV_m using Monte Carlo simulations. The simulations allow parametric effects to be studied ex situ and initial optimization to be performed.

Information on the tablet centroid location (*x*- and *y*- directions), the circulation time (time between successive tablet sightings in the spray zone), the projected surface area of the tablet toward the spray nozzle (or the camera, in this case), and the velocities parallel and perpendicular to the cascading layer of tablets was obtained. Circulation time, defined as the time between successive sightings of the tracer tablet in the spray zone, was calculated as the difference between the time of a tracer tablet's appearance on the surface, in the spray zone, and the time of its previous appearance in the spray zone. It is important to point out that it is possible for the tracer to circulate below the top surface of the cascading layer and not be "seen" by the camera. Since the camera replaces a spray nozzle in the coating operation, the particle will not see the spray during such an event and hence will not get coated. Thus, this experimental technique captures the dynamic nature of the cascading layer, where the particles emerge at the top surface and then may disappear into the lower part of the cascading layer. Any coating-process model in which a particle is assumed to remain at the surface once it emerges will not account for this dynamic nature and thus will not be accurate. Also, this technique allows quantification of the mixing level in the pan and can be used to compare and optimize different baffle designs to achieve optimal mixing.[18]

The projected surface area of the tablet is defined as the surface area of the tablet projected toward the camera as it passes through the spray zone. The amount of coating the tablet receives during each sighting in the spray zone is directly dependent on the projected surface area. The velocity of a tablet in the *x*-direction (the direction perpendicular to the cascading layer of tablets) and the *y*-direction (the direction of the cascading layer of tablets) was calculated by the ratio of displacement (determined from centroid locations) over time. A more detailed discussion of these parameters is provided by Pandey.[2]

The operating variables studied in this work included pan speed (6, 9, and 12 rpm), tablet size (6.3, 7.9, and 10.4 mm), pan loading (2 levels), spray shape, spray area, and spray flux (uniform, non-uniform) inside the spray zone.

Monte Carlo Simulations

There were 2 main inputs required for the Monte Carlo simulations to model the pan coating operation, as shown in Figure 2. The first input was the information characterizing the movement of tablets inside the coater, which was obtained from the video-imaging experiments. This information included centroid location distribution, circulation time distribution, projected surface area distribution of tablets as they passed through the spray zone, and velocity distribution of tablets in 2 directions. The other input was information on the spray dynamics of the system, which included spray area, spray shape, and spray flux distribution in the spray zone. Nozzle type, spray solution properties, atomizing air pressure, inlet air temperature, and tablet bed temperature also affect the spray dynamics of the system but could not be examined within the scope of this work. Some of these factors have a significant role to play in determining the surface roughness of the coating, and have been addressed by the authors in an entirely separate study.[19]

The spray flux distribution within the spray zone was obtained using a patternator (Figure 3), a series of tubes that measure the volume of the spray solution at different locations.[20] The patternator used in the current work was

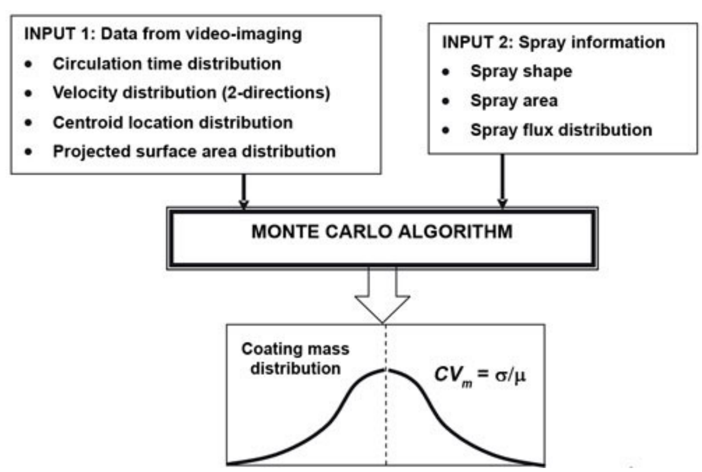

Figure 2. Monte Carlo scheme to estimate mass coating variability.[2]

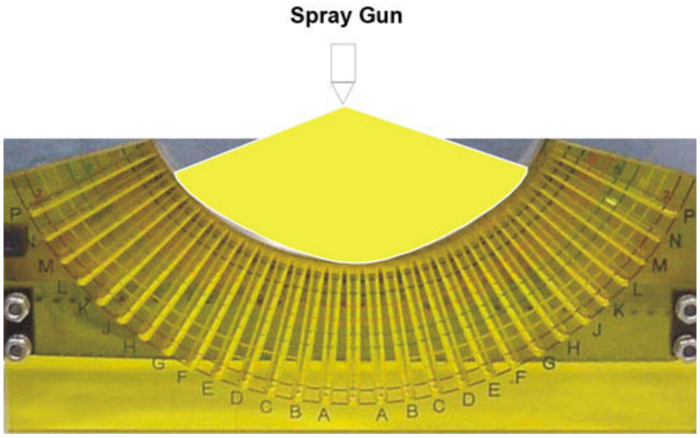

Figure 3. Patternator used to estimate spray flux variation inside the spray zone.

30 cm long, 15 cm high, and 1.5 cm thick and had 27 identical tubes. The volume of spray solution collected in each tube was used to generate a flux profile within the spray zone.

The algorithm used to simulate tablet movement using Monte Carlo simulations is discussed in detail by Pandey et al.[1] In summary, a random start location was selected from the centroid location distribution that was generated from the experimental data. The next tablet location was calculated (Equation 1) from randomly selected *x*- and *y*-velocities chosen from the experimental velocity distribution:

$$y_{j+1} = y_j + v_y \Delta t \;\; ; \;\; x_{j+1} = x_j + v_x \Delta t \qquad (1)$$

where y is the centroid y-location (in the direction parallel to the cascading layer flow) of the tablet, x is the centroid x-location (in the direction perpendicular to the cascading layer flow in the plane of the cascading layer) of the tablet, Δt is the time increment, and v_x and v_y are velocities in the x and y directions. The time is denoted by subscript j, and the time increment used was 40 ms, which is identical to the time the camera takes to record the next location of the tablet. The particle-wall collisions were taken into account and considered to be perfectly elastic.

Spray information, including spray flux distribution, spray area, and spray shape, was mapped onto all of the calculated information. Projected surface area values were randomly chosen from the area distribution generated experimentally. The movement was simulated for all the tablets in the bed for a coating time of 30 minutes, and the weight gain of each tablet was calculated using Equation 2:

$$m_i = \sum_{1}^{n} \sum_{Pass} A_{exp} S_{flux} \Delta t \qquad (2)$$

where m_i is the coating weight gain by tablet i, A_{exp} (mm^2) is the projected surface area at each sighting of the tablet in the spray zone, S_{flux} (mg/mm^2/s) is the spray flux at the centroid location of the tablet, and n is the total number of passes by a tablet through the spray zone.

The coating weight variability between the tablets was calculated using the following equation:

$$CV_m = \frac{\sigma_m}{\mu_m} \qquad (3)$$

where CV_m is the weight gain coating variability or the relative standard deviation of the mass coating distribution, σ_m is the standard deviation of the coating weight gain distribution, and μ_m is the average of the coating weight gain distribution. Each pass was defined by the appearance of the tablet in the spray zone before it disappeared into the bulk of the tablet bed.

Results and Discussion

Weight gain variability in the coating process occurs primarily because all of the tablets in a bed do not behave identically in a given time period. For example, the number of passes each tablet makes through the spray zone is not the same. This was captured by the Monte Carlo simulations and is shown in Figure 4 for 7.9-mm placebo round tablets in a 30-minute coating run at a pan speed of 12 rpm. It is desirable to have a narrow distribution of circulation times between different tablets. This can be achieved by using mixing aids/baffles in the system.[18]

Effect of Coating Time

The effect of coating time on the CV_m is shown in Figure 5. It was found that for 7.9-mm tablets rotating at a pan speed of 12 rpm, CV_m decreased with increasing coating time and

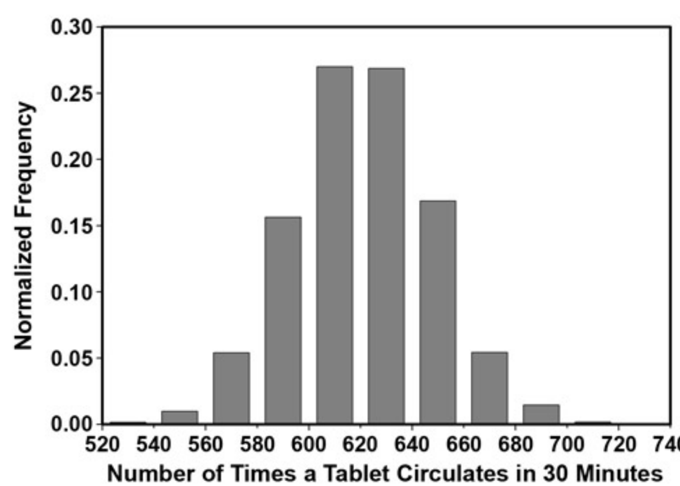

Figure 4. Distribution of number of passes of 7.9-mm tablets in a 30-minute run.

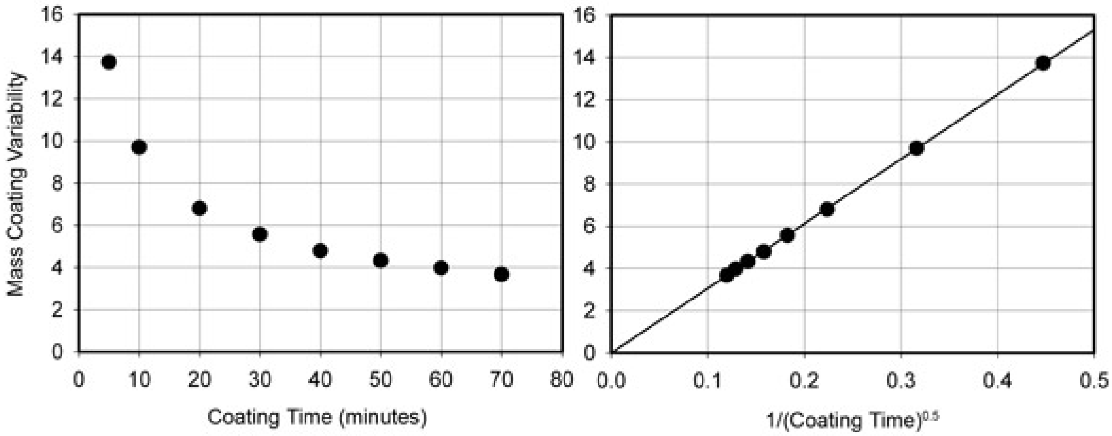

Figure 5. Effect of coating time on mass coating variability for 7.9-mm tablets at a pan speed of 12 rpm.

was inversely proportional to the square root of coating time in accordance with Equation 4:

$$CV_m \propto \frac{1}{\sqrt{t}} \quad (4)$$

where t is the total coating time. This dependence of CV_m on coating time has been reported previously[8,18,21-23] for similar systems, such as fluidized beds and granulators, using renewal theory but has not been reported for pan coaters.

Effect of Spray Shape and Spray Area

Two spray shapes (ellipsoidal and circular) were examined to study the effect of spray shape on CV_m. The spray rates in both cases were kept the same. Initially, the spray area was also kept the same for both cases. This meant that the entire pan width was not covered for the circular spray shape, which allowed "bypassing" of tablets around the spray area, as shown in Figure 6A. This resulted in significantly higher CV_m values in the case of the circular spray shape, which, not surprisingly, shows that it is critical that the spray cover the entire pan width and allow no or minimal bypassing.

To study the effect of spray shape alone, the spray area for the circular and elliptical spray shapes was kept the same and the entire pan width was covered. This was achieved by comparing 2 circular-shaped spray regions with 1 elliptical spray region, as shown in Figures 6B and 6C. The ratio of the minor axis of the ellipse to the major axis was kept at 0.5, to maintain the same total spray area. Figure 7A compares the results for the 2 spray shapes for 10.4-mm tablets at a fractional fill volume of 0.10 at 3 different pan speeds. It is clear that the spray shape does not significantly influence the mass coating variability, as long as the spray area is kept the same. An effect of spray shape (circular vs elliptical) on coating quality (roughness) has been discussed by Porter,[24] who concluded that a circular spray pattern produces smoother and glossier tablets but results in a greater chance of localized overwetting, in comparison to the elliptical spray pattern.

In addition, cases with spray covering the entire pan width but with different spray areas were compared. The circular-shaped (higher spray area) spray was found to give better uniformity compared with the ellipsoidal shape (area of circle/area of ellipse = 4, in this case). Thus, the mass coating variability was reduced with an increase in spray area, as

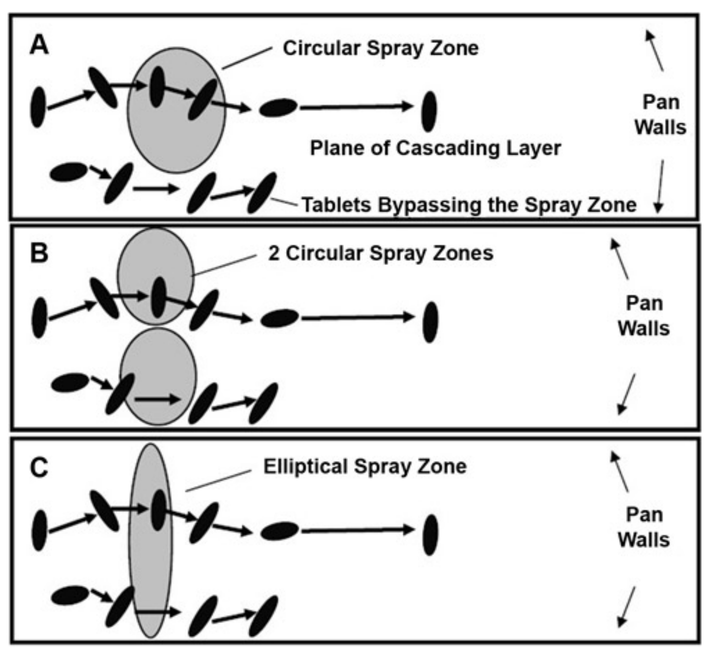

Figure 6. Schematic of the different spray shapes or regions studied using Monte Carlo simulations. Part (A) shows circular-shaped spray region that does not cover the whole pan width; (B) shows 2 circular-shaped spray regions with the same spray area as that of the elliptical-shaped spray region shown in (C).

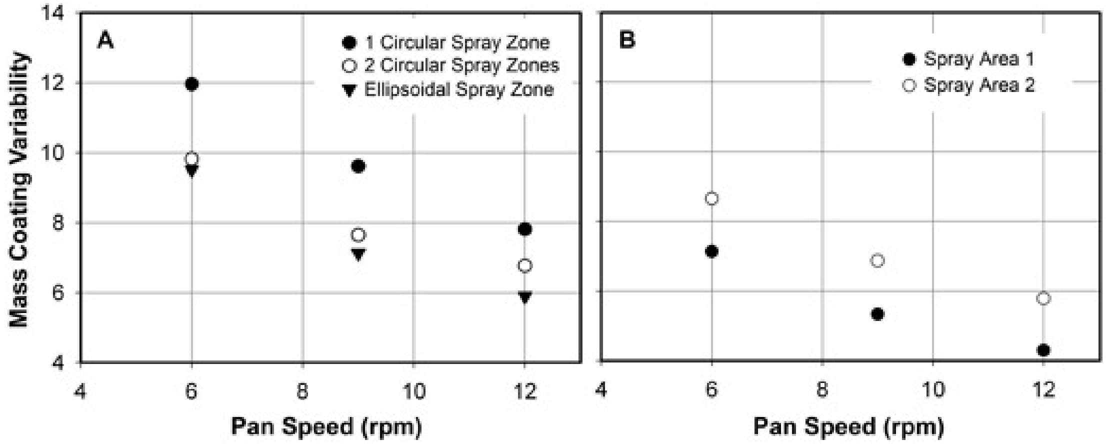

Figure 7. (A) Effect of spray shape on mass coating variability for 10.4 mm tablets at 3 different pan speeds. (B) Effect of spray area on mass coating variability for 7.9 mm tablets at 3 different pan speeds.

shown in Figure 7B for 7.9-mm tablets. These results were observed for all 3 sizes (6.3, 7.9, and 10.4 mm) of round placebo tablets tested.

Effect of Pan Loading, Pan Speed, and Particle Diameter

The average weight gain (μ_m) of tablets in a coating process is given by the following equation:

$$\mu_m = \frac{Spray\ \ flux(g/s/mm^2) \times Spray\ \ area(mm^2)\ \times\ t(s)}{N} \quad (5)$$

where N is the number of tablets in the pan and t is the total coating time.

The factors known to affect the CV_m of the process can be broadly classified into 2 groups: tablet movement dynamics and spray dynamics. Tablet movement dynamics are primarily a function of tablet velocity, tablet physical properties (eg, size), pan loading or number of tablets in the pan, pan size, and mixing inside the pan. Spray dynamics are primarily a function of droplet size, gun-to-bed distance, fluid properties, drying air temperature, spray area and shape, and spray flux variation inside the spray area.

In this study, the effects of tablet movement and some aspects of spray dynamics on mass coating variability were investigated. The variables governing tablet movement can be reduced further to the set of independent variables (for this experimental design). For example, the tablet velocity has been shown to be a function of pan radius (R), pan speed (ω), particle diameter (d_p), and pan loading, as expressed in Equation 6.[8] The pan loading was quantified by using fractional fill volume (υ), defined as the ratio of the volume of the bed to the total pan volume, shown in Equation 7. Two levels ($\upsilon = 0.10$ and $\upsilon = 0.17$) were used, covering the range of typical pan loadings used in the coating industry. Fractional fill (υ) volume is a function of the number of tablets in the pan, the pan radius, and the particle diameter:

$$V = kR\omega^{0.67}\left(\frac{g}{d_p}\right)^{0.17}\upsilon^{1.8} \quad (6)$$

$$\upsilon = \frac{Volume\ \ of\ Bed}{Pan\ \ Volume} \quad (7)$$

Therefore, the main (independent) variables governing tablet movement and thereby CV_m are d_p, ω, R, and N. All the experiments performed in this study were on a 58-cm-diameter pan, and hence the pan radius effect was not studied. Thus, CV_m is a function of d_p, ω, and N for a given pan radius, as shown in Equation 8, where a, b and c are real numbers and k_1 is a constant. A regression analysis from the Monte Carlo simulation results was performed on the results obtained from the above-discussed experimental matrix (3 tablet sizes, 3 pan speeds, 2 pan loadings).

$$CV_m\ = k_1\ d_p^a \omega^b N^c \quad (8)$$

A statistical analysis of all the results was conducted using JMP (SAS Institute, Cary, NC) software. It was observed that CV_m was significantly dependent on d_p ($P < .0001$), ω ($P = .0002$), and N ($P < .0001$) and there were no significant interaction effects between these variables ($P > .05$). The CV_m was directly proportional to d_p and N and inversely proportional to ω. Thus, if the particle size is decreased, then the coating uniformity will improve, if all other parameters are kept constant. A possible reason for this is the increase in the number of particles inside the spray zone. An increase in pan speed results in a better-mixed system, thereby reducing the mass coating variability. The

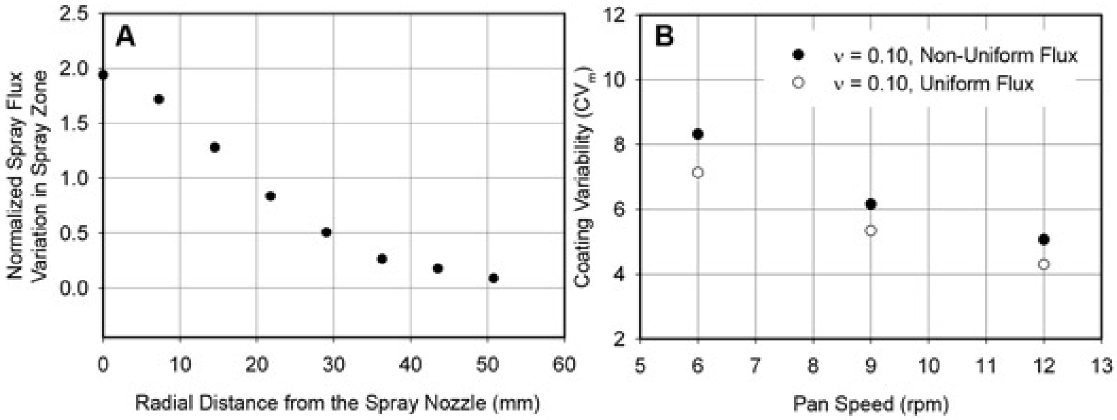

Figure 8. (A) Normalized spray flux distribution in the spray zone with radial distance at 40 psi atomizing air pressure and 10.2 cm gun-to-bed distance. (B) Comparison of CV_ms between uniform and non-uniform spray flux for 7.9-mm tablets, at 2 different pan loadings and 3 pan speeds.

exponents *a*, *b*, and *c* were determined from statistical analysis using JMP and are shown in Equation 9:

$$CV_m = k_2 \frac{d_p^{1.2} N^{0.5}}{\omega^{0.4}} \tag{9}$$

where k_2 is a constant.

Good agreement ($R^2 = 0.93$) was obtained between the values predicted from this model (Equation 9) and the CV_m values predicted by the Monte Carlo simulations. When the effect of coating time (Equation 9) is incorporated and Equation 4 is used, Equation 10 is obtained:

$$CV_m = k_3 \frac{d_p^{1.2} N^{0.5}}{\omega^{0.4} t^{0.5}} \tag{10}$$

where k_3 is a constant.

Effect of Spray Flux Variation Inside the Spray Zone

Spray flux variation inside the spray zone was measured using a patternator. The spray gun used was a 2-fluid air-atomizing nozzle (model 1/8JAC+SU11) from Spraying Systems (Wheaton, IL). A fourth-order polynomial was fit ($R^2 = 0.999$) to the data obtained from the patternator (normalized data shown in Figure 8A) and used in the Monte Carlo simulations. The atomizing air pressure used for this experiment was 40 psi, with a gun-to-bed distance of 10.2 cm (4 inches). Figure 8B shows the results for 7.9-mm tablets, at 2 different pan loadings. The uniform spray flux (no variation within the spray zone) was found to yield a lower CV_m than that produced when spray flux varied with respect to location (non-uniform flux) inside the spray zone. It should also be noted that the value of CV_m decreased with an increase in pan speed, as shown in Figure 8B. Better mixing is obtained at higher pan speeds, which results in lower weight gain variability during coating.

Model Verification by Coating Experiments

To verify the predictions of CV_m from the Monte Carlo simulations, experimental coating runs were conducted at the same conditions. The pan coater used in this study was the same one (a thin pan coater) that was used to conduct the video-imaging experiments. The coating experiments were conducted at 2 pan speeds (6 and 12 rpm) and at 2 pan loadings (= 0.10 and = 0.17). Ethyl cellulose (EC) was used as the coating material. The spray gun used was the same one used to generate the spray flux profile using the patternator. Black polystyrene spheres 9 mm in diameter were used for the experiments. To estimate coating weight gain CV_m, ~90 white polystyrene spheres were introduced into the system.

A 12% solids coating solution with ethanol as the solvent was used as the spraying medium. The coating run was conducted for 30 minutes. The atomizing air pressure was maintained at 40 psi, and the spray rate was 15 mL/min. The gun-to-bed distance was 10.2 cm (4 inches). To facilitate drying, air was circulated in the pan by using an external port connected to a vacuum. The entire pan setup was placed inside a fume hood for safety reasons. EC-coated white spheres were isolated from the system after the coating run. They were then weighed individually to estimate their weight after coating. The coating on each sphere was then removed by using ethanol. The spheres were then dried and weighed again to estimate the weight of the sphere before coating. The weight gained during coating by each sphere was calculated as the difference between the weight before and the weight after coating.

A total of ~90 white spheres were recovered from each coating run. The CV_m of the coating run was estimated using

Table 1. Experimental CV_m Results for 4 Operating Conditions and 1 Repeat Run for 9-mm Polystyrene Spheres

Pan Loading (Fractional Fill)	Pan Speed (rpm)	Experimental CV_m (%)
0.10	6	18.35
0.10	12	12.88
0.17	6	23.95
0.17	6	26.12
0.17	12	21.90

the coating weight gain of these 90 spheres. Four operating conditions were used for the coating runs. One of the coating runs was replicated to check the repeatability of the process. The operating conditions and the corresponding experimentally obtained CV_ms are shown in Table 1. As evident from Table 1, the CV_m decreased with an increase in pan speed and a decrease in pan loading. This is consistent with the trends predicted by the Monte Carlo simulations (Equation 10).

To effectively compare the CV_m predictions from the Monte Carlo simulations with those from the experiments, the exact experimental conditions must be taken into account. This meant that there needed to be 2 additional considerations, the spray area dimensions and the pulsing of the nozzle.

Spray Area Dimensions

To estimate the exact dimensions of the spray area, a target composed of a piece of foam sponge was kept under the spray gun at the same location as the table bed. The spray

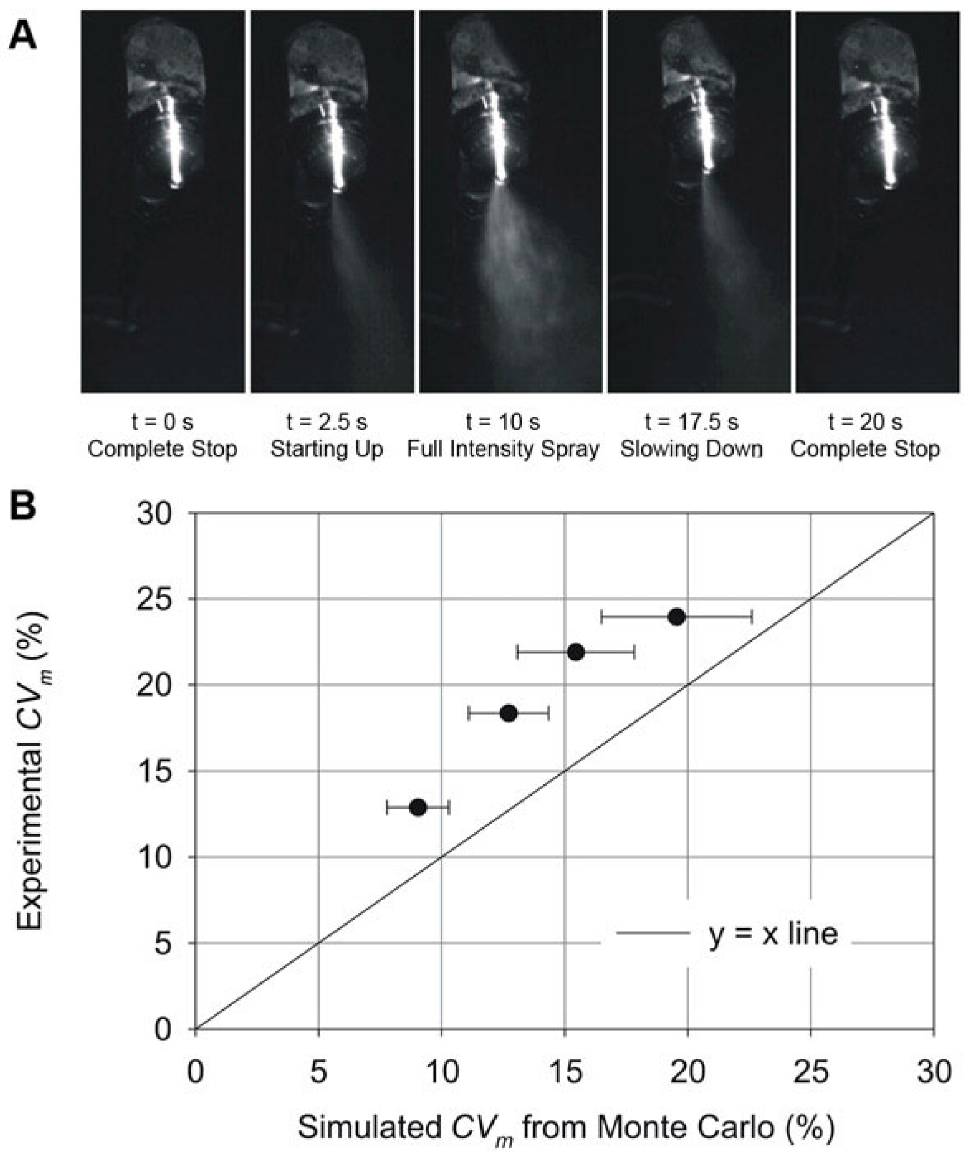

Figure 9. (A) Snapshots of spray nozzle with time to show a sample of the pulsing of the nozzle. (B) Comparison of CV_ms obtained from experiments and Monte Carlo simulations.

was then started and the dimensions of the spray area on the sponge were measured. These dimensions were then used in the Monte Carlo simulations to match the experimental spray area. The spray area was elliptical and did not cover the entire width of the pan.

Pulsing of Nozzle

It was observed during experiments that the spray nozzle was not delivering the spraying solution at a constant rate and there was a pulsing effect: the nozzle sprayed solution for a period and then stopped spraying for a shorter period before turning back on again, as shown in Figure 9A. This can be attributed to a solids buildup during spraying. The pulsing was taken into account in the Monte Carlo simulations. A high-speed camera (1000 frames/s) was used to record a video of the nozzle during spraying to quantify the pulsing rate of the nozzle. An analysis of the video showed that, on average, the nozzle sprayed for 75% of the total time.

The spray area dimensions and the pulsing of the nozzle were taken into account in the Monte Carlo simulations, and the values of CV_m were compared with the experimental values (Figure 9B, for the 4 experimental conditions). The error bars in Figure 9B show twice the value of the standard deviation. The standard deviations for the simulations were obtained by randomly sampling 90 points from the weight gain distribution predicted by the Monte Carlo simulations for all of the particles in the system. This procedure was repeated 100 times to estimate the error bars shown in Figure 9B. The Monte Carlo simulations underpredicted the value of CV_m in comparison to the experimentally obtained CV_m. It should be noted that the Monte Carlo simulations are based on observations from a single tracer particle that was used in the video-imaging experiments. Hence, it was assumed that the movement of the tracer particle is representative of the movement of all the particles in the system. Even though this is a good assumption for the current case, as is confirmed by some of the DEM results,[8] the assumption does not hold true for all of the particles in the system. The experimental CV_m, on the other hand, is based on the weight gain of 90 individual spheres. It is very likely that the tracer particle does not perfectly represent the movement of all of these particles. This may, in part, explain the disparity between the experiments and the simulations. In addition, the video-imaging experiments were conducted in a dry environment (no liquid spray), whereas the coating experiments were conducted in a wet environment. Even though an earlier work[25] showed that the presence of ethanol in the system does not make a significant difference in the particle motion, the coating experiments were done using a more viscous solution (12% wt/wt EC/ethanol). This could have affected the motion of particles and caused a disparity between the simulations and the coating experiments.

CONCLUSIONS

This study demonstrates that Monte Carlo simulations can be used effectively to predict the mass coating variability in pan coating devices. The model developed can provide a basis for adjustments in process parameters required during scale-up operations. The same methodology may be applied to any coating system in any size drum once key parameters have been established for the equipment.

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