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Movement of Different-Shaped Particles in a Pan-Coating Device Using Novel Video-Imaging Techniques

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ABSTRACT

The purpose of this study was to investigate the effects of particle shape on the movement of particles in a pan-coating device using novel video-imaging techniques. An area scan CCD camera was installed inside a 24-in pan coater at the same location as that of a spray nozzle, and the movement of particles was tracked using machine vision. A white tracer particle was introduced inside a bed of black-coated particles. The effects of pan loading, pan speed, and particle shape on the movement of particles was studied. The response variables were circulation time, surface time, projected area of particle per pass, dynamic angle of repose, cascading velocity, and dispersion coefficient. Experiments were conducted at 3 different pan speeds, 6, 9, and 12 rpm, and 2 fill levels (ratio of bed depth to pan diameter), one eighth and one quarter, and data were collected over a 30-minute time period. The differences in circulation times of spheres and tablets, with similar volume equivalent diameter as that of the sphere, were found to be insignificant at the 95% confidence interval. The circulation time ranged from 2.8 to 10.8 seconds depending on the operating condition and increased with increasing pan load and decreasing pan speed. The distributions of circulation time, surface time, and projected surface area were found to be nonnormal. The dynamic angle of repose for tablets was higher than for spheres. Also, the bed surface for spheres was much flatter in comparison with tablets where the bed shape attained a "wave-like" form. The average velocity of tablets in the cascading layer was found to be significantly higher than spheres. A linear model (R^2 > 0.98) best described the variation of velocity as a function of pan speed for all of the operating conditions.

KEYWORDS: pan coater, tablet movement, circulation time, particle shape, tablet velocity

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INTRODUCTION

The uniformity of coating applied to large particles and tablets in a pan-coating device is of significant interest to the pharmaceutical industry. The coating of solid-dosage forms, such as capsules, granules, and tablets, is conducted for a variety of reasons, such as to mask the unpleasant taste or odor of the drug, protect it from the environment, provide a means for identification, and sometimes to control the bioavailability of the drug (sustained or enteric). Coating of small particles is often conducted in fluidized beds, but tablets are not generally coated in fluidized beds because of the mechanical damage that occurs in the device. When coating tablets or particles in a pan coater, the occurrence and duration of particles at the surface of the cascading bed determines how much spray material an individual particle receives during a pass through the spray zone. The regularity with which particles pass through the spray plays an important role in determining the overall uniformity of coating for the batch of material being coated.[1] To improve coating performance, it is essential to understand the movement of particles inside a pan coater and the factors that control it. The main factors that control this movement are pan speed, pan loading, tablet shape and size, and presence/absence of mixing aids (baffles).

Various experimental techniques (mostly particle tracking), as well as models (mostly using the discrete element method [DEM]), have been used in the past to study particle motion inside particulate systems. In one of the early experimental studies, the tablet appearance times were studied[2] by photographic and manual counting methods using a bed containing different-colored tracer tablets. The experiments were conducted on a 60-cm Accela-Cota. An average circulation time of 25 seconds and a range of 2 to 243 seconds were reported. Leaver et al[3] used light emission from a single luminous tablet to study the particle movement. Their experiments on a 60-cm Accela-Cota (Manesty Machines plc, Liverpool, United Kingdom) showed that both the surface time (time spent by the particle on the surface) and circulation time (time spent in the bulk of the bed) decreased with increasing drum speed and loading. The run time in their experiments was 15 to 20 minutes. The authors reported average circulation times between 2 and 14 seconds, and average surface times between 5 and 300 ms, for experiments with different tablet sizes (7.5, 9, and 11 mm), drum speeds (6, 9, and 12 rpm), and drum loadings (6, 8, and 10 kg). A positron emission particle tracking technique was used to track a radioactively labeled tracer particle in a rotating drum by Parker et al.[4,5] An active surface layer approximately two-thirds as thick as the underlying bed layer was observed in all of the cases.

Nakagawa et al[6] used a magnetic resonance imaging technique to analyze the particle movement in a rotating horizontal cylinder. It was found that the thickness of the flowing layer increased with increasing speed of rotation. Results from this work were compared with DEM simulations by Yamane et al[7] and were in good agreement when the coefficient of friction and sphericity in the simulation were adjusted to give the best fit. Some researchers have used digital images with postprocessing software to study the movement of particles inside a coater.[8-10] One disadvantage of the technique is that it leads to very large data files of images to be postprocessed. Jain et al[11] used particle-tracking velocimetry to study the velocity field within the fluidized layer of particles in a rotating tumbler. The granular flow was illuminated by a laser flash and recorded by a standard particle imaging velocimetry system with a CCD camera. It was found that the normalized streamwise velocity profile was linear throughout the fluidized layer and became logarithmic as particles entered the "fixed" bed. DEM simulations have also been used to study the movement of tablets in a rotating drum.[7,12-14]

The current work focuses on a novel video imaging technique.[1,15,16] This technique is best described in Sandadi et al.[16] In brief, an area scan CCD camera (Pulnix 1020-25, Pulnix Inc, Sunnyvale, CA) is mounted inside the pan coater in approximately the same position as the spray gun and adjusted to scan a region covering the normal spray zone area during a coating operation. A white tracer particle is placed in a bed of black particles. The tracer tablet is identified using Machine Vision Software (Sherlock 32, Coreco Imaging, Bedford, MA). The software is programmed to identify and record the area and location of the centroid of the tracer tablet. The total processing time for the algorithm is in the range of 20 to 30 milliseconds, and the new frame or field is then grabbed 40 milliseconds after the previous frame. A major advantage of this technique is that the full frames of image data need not be stored for postprocessing, and a 30-minute experiment typically generates a data file of size 40 to 60 kb. This technique enables in situ, near real-time acquisition of particle motion in the coater and can be used to evaluate various parameters that characterize the particle motion. These parameters include the following: (1) circulation time, τ_{circ}, which is the time between successive tablet sightings at the bed surface; (2) surface time, τ_{surf}, which is the time that the particle spends within the spray zone; (3) projected surface area, A_{tab}, which is the surface area of tablet exposed toward the spray nozzle; (4) surface velocity, V_y, which is the velocity parallel to the direction of flow of the cascading layer; (5) dynamic angle of repose, θ; and (6) dispersion coefficient, D_x, which characterizes the movement at the surface in the axial direction.

In a previous study,[16] most of these parameters were evaluated for tablets. It was found that the average circulation time varied in the range of 2.9 to 15.5 seconds and the surface time in the range 0.06 to 0.2 seconds, for the conditions studied. Decreasing trends for circulation and surface times were observed with increasing pan speeds, pan loadings, and tablet size. The axial dispersion coefficient was found to lie in the range of 0.2×10^{-3} to 4×10^{-3} cm^2/second and was found to increase with increasing pan speed.

The current study is an extension of the previous work, concentrates on the movement of spherical particles in a

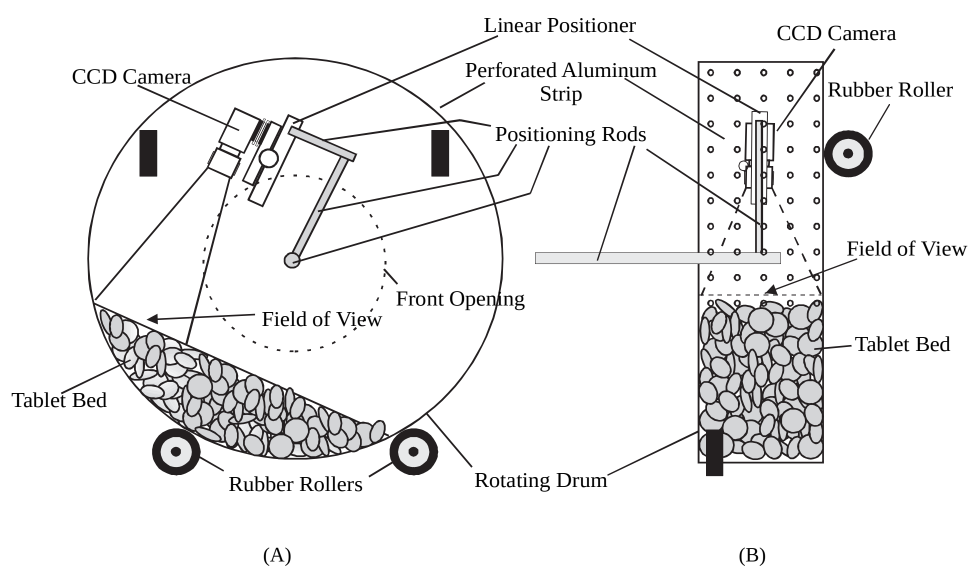

Figure 1. Experimental set-up of the 24-in pan coater used in this study. (A) side view; (B) end view.[16]

Table 1. Experimental Matrix

Variable	Level 1	Level 2	Level 3
Pan loading (fill)	1/8	1/4	–
Pan speed (rpm)	6	9	12
Particle size (mm)	6.3	7.9	10.4
Particle shape	Standard round placebo	Spherical (9 mm)	–

pan coater, and compares their movement with tablets. This information will give valuable insights into the effect of particle shape on particle movement in a pan coater and help address some scale-up questions.

MATERIALS AND METHODS

A full description of the perforated pan coater used in this work is given in Turton and Sandadi.[15] In summary, the pan consists of 2 transparent Plexiglas discs, 60 cm outer diameter and 57.5 cm inner diameter, separated by a 10-cm perforated aluminum strip, as shown in Figure 1. The perforated strip enables air to be drawn through the tablet bed using suction, which promotes the drying of solvent. The pan is rotated about its axis using a stepper motor controlled by a feedback speed controller. Pan speed can be adjusted continuously from 1 to 30 rpm. The lens used in the camera was a 12.5-mm macro lens (Image Labs International, Bozeman, MT). A flexible fiber-optic light guide that fits onto the end of the lens provides light inside the pan. The baffles used were placed at an angle of 45° with the wall of the pan in a plough arrangement and were 14.14 cm in length and 1.41 cm in height. The particles used in this study were 9-mm diameter polystyrene spheres with a particle density of 0.99 g/mL. A white polystyrene sphere tracer was introduced in a bed of black spheres. The properties of the tracer particle, except color, were identical to that of the black particles. The 3 sizes of tablets used by Sandadi et al[16] were standard round placebo tablets with diameters of 6.3, 7.9, and 10.4 mm with a particle density of 1.2 g/mL. The tablets were first coated to a 4% theoretical weight gain using Black Opadry (Colorcon, West Point, PA) and then coated to a 0.25% theoretical weight gain using Clear Opadry (Colorcon). The tracer tablets were produced by coating the placebo tablets with Clear Opadry to 4.25% theoretical weight gain. To effectively compare tablets with spheres, a volume equivalent diameter of the tablet, defined as the diameter of a sphere with the same volume as that of tablet, was evaluated. The volume equivalent diameter of the 10.4-mm tablets was 8.9 mm, which for the tablets used was the closest to the diameter of the spheres (9 mm).

The experimental matrix was designed to study the effect of the operating conditions on the movement of the particles (Table 1). The 3 levels of pan speed studied were 6, 9, and 12 rpm. The pan loading was varied at 2 levels, one-eighth and one-quarter fill (fill level is defined as the ratio of particle bed depth to pan diameter). These experimental conditions were identical to ones used to evaluate tablet movement by Sandadi et al.[16]

Measurement Techniques

Circulation Time (τ_{circ})

The circulation time is defined as the time between successive initial sightings of the tracer tablet in the region of interest (ROI) that is longer than some cut-off time.[16] For all of the experiments, the ROI was an area approximately 10-cm square located in the middle of the top half of the cascading layer. The cut-off time was varied over a wide range, and the effect on the results was studied. The variable examined was the total number of times the tracer particle circulated (number of passes) on the surface in a 30-minute time period as predicted by different cut-off times. A typical graph obtained by such an analysis is

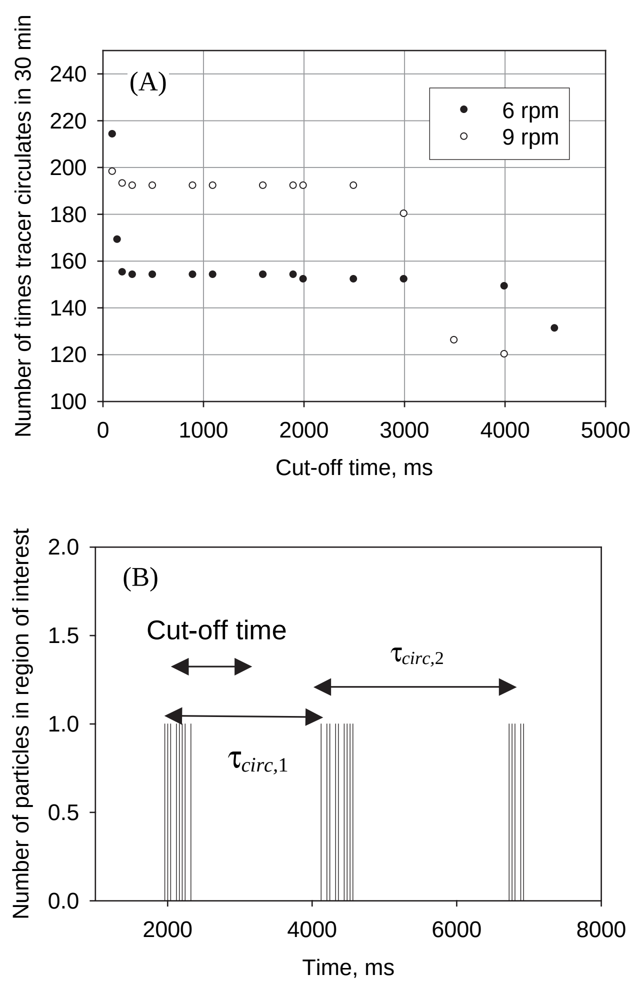

Figure 2. Estimation of cut-off time to determine circulation time. (A) typical cases for one-fourth fill at pan speeds of 6 and 9 rpm; (B) raw data for a one-eighth fill at 12 rpm for 9-mm polystyrene balls.

shown in Figure 2A. As seen in Figure 2A, the number of passes initially decreases rapidly with an increase in cut-off time, then it remains almost constant for a wide range of cut-off times, and finally it decreases rapidly again. When the cut-off time is too low, the analysis considers all of the individual sightings as a new pass; hence, the calculated number of passes is high. When cut-off time is too high, 2 or more separate passes are considered to be part of the same pass, giving rise to a decrease in the calculated number of passes. The number of passes was found to remain steady in the range of 400 to 1800 milliseconds, and any value in this range will effectively separate a "new" circulation or pass from multiple sightings in the same pass. A cut-off time of 500 milliseconds was chosen for subsequent analysis. It should be noted that this cut-off is a function of the operating conditions, such as pan loading, pan speed, and presence/absence of baffles, and must be examined for each operating condition. Figure 2B shows a typical set of raw data for one-eighth fill at 12 rpm for 9-mm polystyrene spheres.

Surface Time (τ_{surf})

This is defined as the time that the tracer particle spends on the surface in the ROI. The surface time, along with the exposed tablet area, determines the amount of spray a tablet receives when it passes through the spray zone on the surface of the bed. This is estimated by the product of the number of frames for which the tracer is seen in the ROI per pass and the time duration of each frame (40 milliseconds).

Projected Surface Area per Pass

This is defined as the total surface area of the tablet projected toward the camera during each pass through the ROI.

Velocity (V_y)

This is defined as the velocity of the tracer particle parallel to the direction of flow of the particles in the cascading layer. This is determined using the centroid location and time of the tracer particle between 2 successive observations.

Dynamic Angle of Repose (θ)

This is defined as the angle the surface of the bed forms with the horizontal axis, as the pan rotates. It should be noted that the surface of the bed is not a straight line. Because a spray gun is typically focused on the top portion of the bed surface (where the camera is focused), the angle θ is the one measured and reported in this work. Digital images of the cascading layer were taken from a camera, placed outside the coater, and postprocessed to obtain this angle.

Dispersion Coefficient (D_x)

This parameter was used to describe movement of the particle along the axis of the pan. It was estimated using Einstein's "random walk" theory.[16,17] Over a period of time, the variance of the displacement of a particle is directly proportional to time.[18] If x is the axial displacement of the tracer particle, then the variance of this distribution ($\langle x^2 \rangle$) can be used to estimate the value of D_x from the relation: $\langle x^2 \rangle = 2D_x t$. Visual Basic codes were written to determine all of the above parameters.

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. Because the camera replaces a spray nozzle in a coating operation, the particle will not see the spray during such an event and, hence, will not get coated. Thus, the current 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 model developed for the coating process, where a particle is assumed to continue to remain at the surface once it emerges, will not predict the coating uniformity accurately.

Results and Discussion

The run-time for each of the experiments was 30 minutes, and all of the runs were randomized and replicated. As expected, the average circulation time was found to decrease with increasing pan speed, because particles move faster and come back to the spray region sooner, as shown in Figure 3A. The circulation time was found to increase with increasing pan loading, as shown in Figure 3A. As the pan loading increases, the number of particles in the coater increases; therefore, the probability of each particle being in the spray zone decreases, causing an increase in the measured circulation time. The 95% confidence intervals, represented by the error bars in Figure 3A, were seen to decrease with increasing pan speed. The error bars were observed to be smaller at higher pan speeds, which implied that the tracer presented itself in the spray zone in a more uniform manner, suggesting better mixing at higher speeds. This was found to hold true for the other variables, such as surface time and projected surface area per pass. However, the effect was more prominent at the lower pan loading.

The average circulation time of the spheres was compared with that of the tablets used by Sandadi et al.[16] The difference in the circulation times of spheres and 10.4-mm diameter tablets was not found to be significant at a confidence level of 95%, as seen in Figure 3A. The slightly lower

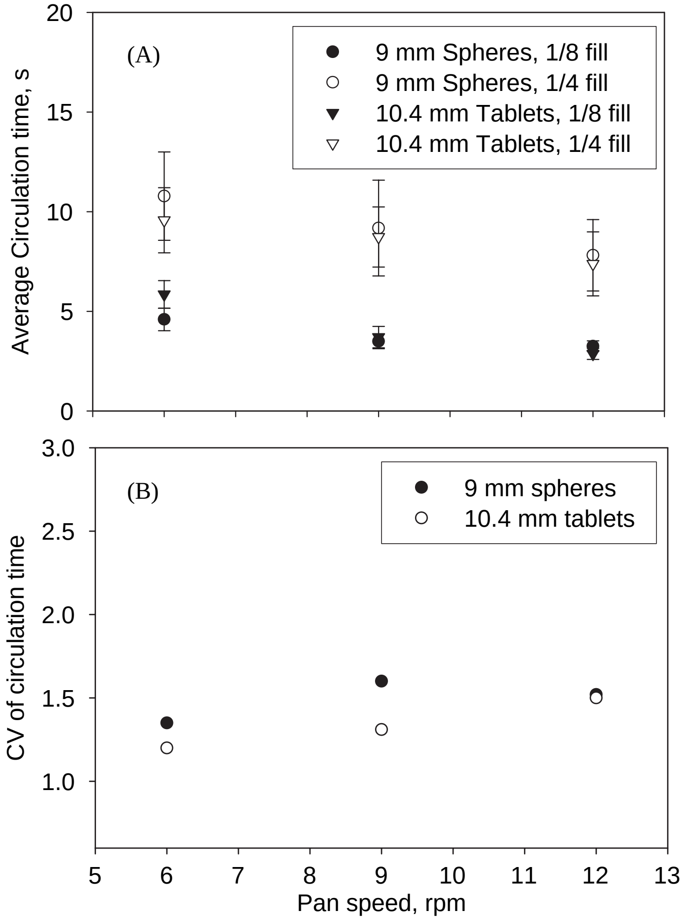

Figure 3. (A) Average circulation time as a function of pan speed and pan loading for 9-mm polystyrene spheres in comparison with 10.4-mm diameter tablets; bars, 95% confidence intervals of the average values. (B) Comparison of coefficient of variation of circulation times for 10.4-mm tablets with spheres for one-fourth fill level.

average circulation times for tablets can be attributed to the lower number of tablets (approximately 6,300) in comparison with spheres (approximately 7,500) for the same fill level (one-fourth fill) of the pan. The coefficient of variation (CV) is a measure of the spread of the distribution and is calculated as the ratio of standard deviation (SD) to average circulation time. Figure 3B shows a comparison of CVs for circulation times between tablets and spheres at one-fourth fill pan loading. The CV for circulation time of tablets (10.4 mm) appears to be slightly lower than spheres at low pan speeds, but, in general, the CV values for spheres and tablets are not significantly different. The slightly lower CV value for 10.4-mm tablets could be because of the lower number of tablets, which achieve better mixing at lower pan speeds, in comparison with spheres for one-fourth fill level.

The average surface time or the time per pass for which the particle receives coating was found to increase with decreasing pan speed and decreasing pan load, as shown in Figure 4A. Figure 4A also shows a comparison of the surface times between spheres and tablets for one-eighth and one-fourth fill levels of pan. The surface time for tablets were found to be significantly lower than spheres for the one-eighth fill case, indicating that tablets spend less time on the surface. The differences were not significant for the one-fourth fill level. The average projected surface area per pass of the tracer was found to decrease with increasing pan speed, as well as pan loading, as shown in Figure 4B. Typical distributions of circulation times, surface times, and projected surface area per pass are shown in Figures 5A–C, respectively, for spheres at a pan speed of 9 rpm and one-eighth fill. It is evident from these figures that these distributions are not Gaussian.

For spheres, the average velocity (V_y) in the direction parallel to cascading flow was found to increase with increasing pan speed and pan loading, as shown in Figure 6. A linear model fits the data very well with a slope of 3.1 and R^2 value of 1.00 for one-fourth fill case and a slope of 2.00 and R^2 value of 0.98 for the one-eighth fill. Figure 6

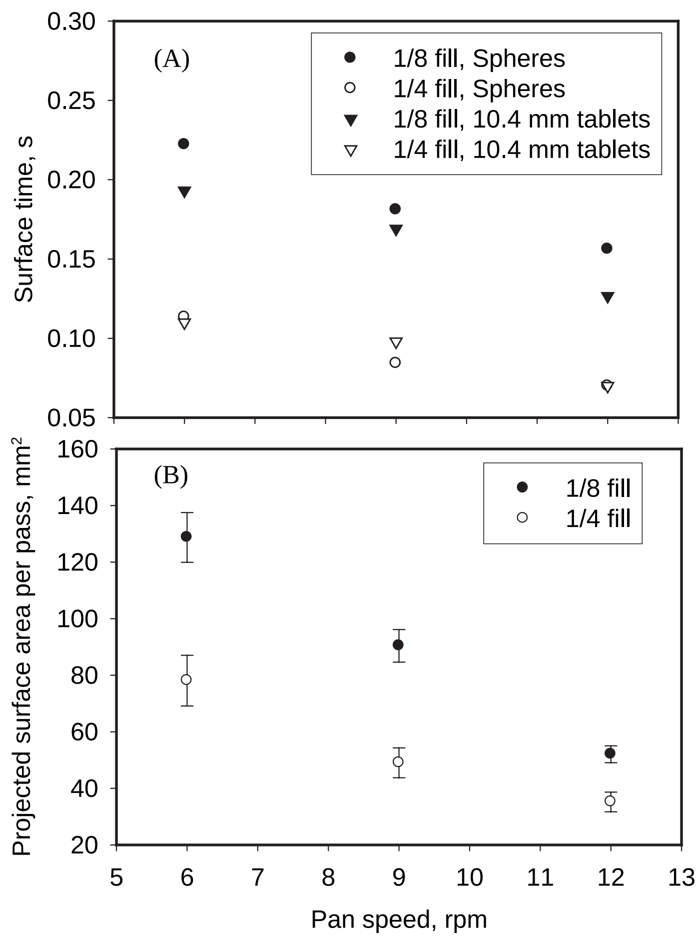

Figure 4. (A) Average surface time as a function of pan speed and pan loading for 9-mm polystyrene spheres; bars, 95% confidence intervals. (B) Average projected surface area per pass as a function of pan speed and pan loading for 9-mm polystyrene spheres; bars, 95% confidence intervals.

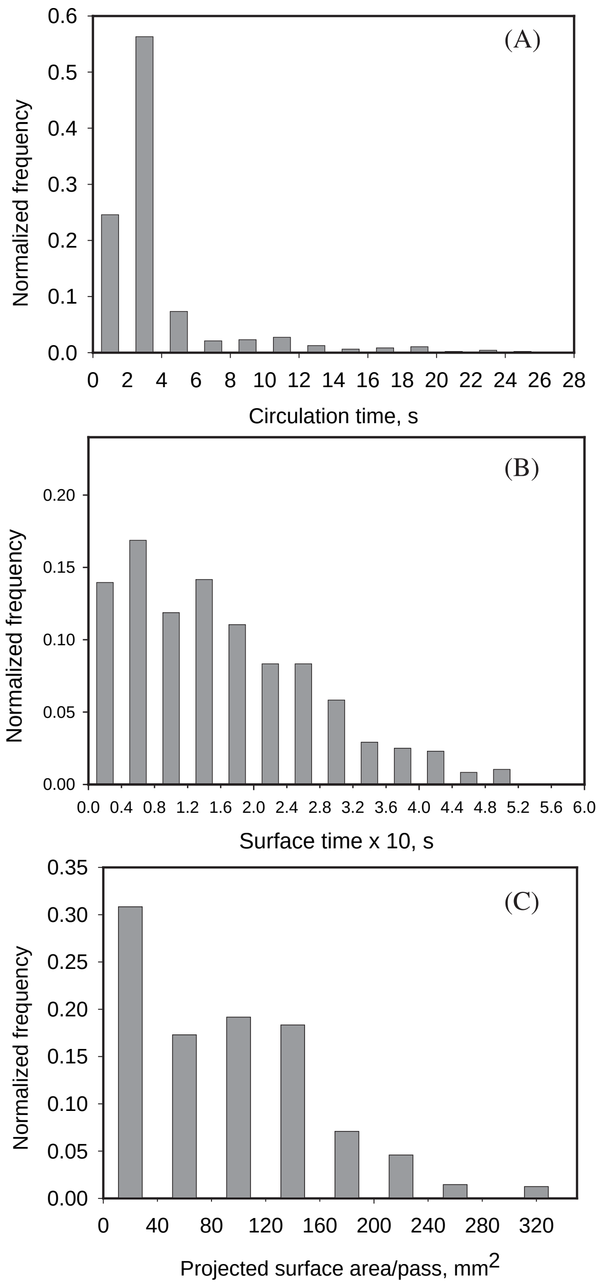

Figure 5. Distributions of (A) circulation time, (B) surface time, and (C) projected surface area per pass, at a pan speed of 9 rpm and one-eighth fill for polystyrene spheres.

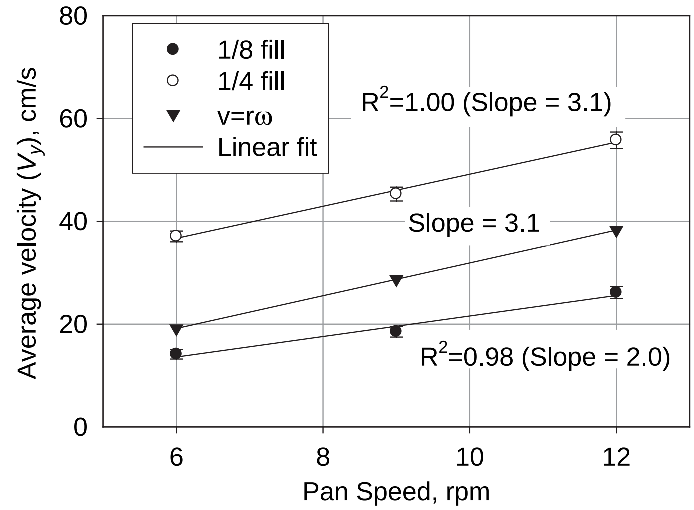

Figure 6. Average velocity parallel to the direction of flow of cascading layer as function of pan speed and pan loading for polystyrene spheres; bars, 95% confidence intervals. A linear model provides a good fit to the experimental values.

also compares the linear velocity (v), given by $v = r\omega$ (r is the pan radius and ω is the pan speed), with experimentally measured values. The comparison demonstrates that linear velocity might be a good indicator of the velocity at some intermediate fill level of the pan because of similarity in trends but fails to give the exact values for one-eighth and one-quarter fill. This information is valuable when scaling up a pan coating process. Leaver et al[3] and Sandadi et al[16] postulated that the cause of the increase in average velocity with pan loading is the increase in dynamic angle of repose. To verify this, the dynamic angle was measured for all of the conditions and is shown in Figure 7. In general, the dynamic angle was found to increase with increasing pan speed and pan loading. There was no significant difference in the dynamic angle between the tablets of the 3 sizes (6.3, 7.9, and 10.4 mm) studied by Sandadi et al,[16] and, hence, the angles reported here are only for 7.9-mm-diameter round tablets. For all of the cases, the dynamic angles were higher for tablets than for spheres.

The average velocity of the tablets was found to be higher than that of spheres, as seen in Figure 8. The difference is more prominent for the one-eighth fill case compared with one-fourth fill. As can be seen from Figure 8, for all of the cases the variation of average velocity as a function of pan speed appears to be linear. The R^2 value for 10.4-mm tablets was found to be 1.00 for both fill levels. The slopes of the linear fit were estimated to be 2.58 and 2.89, respec-

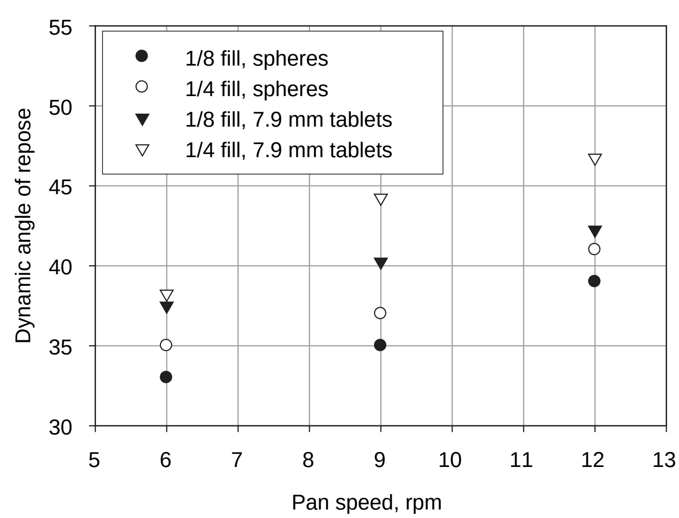

Figure 7. Dynamic angle of repose as a function of pan speed, pan loading, and particle shape.

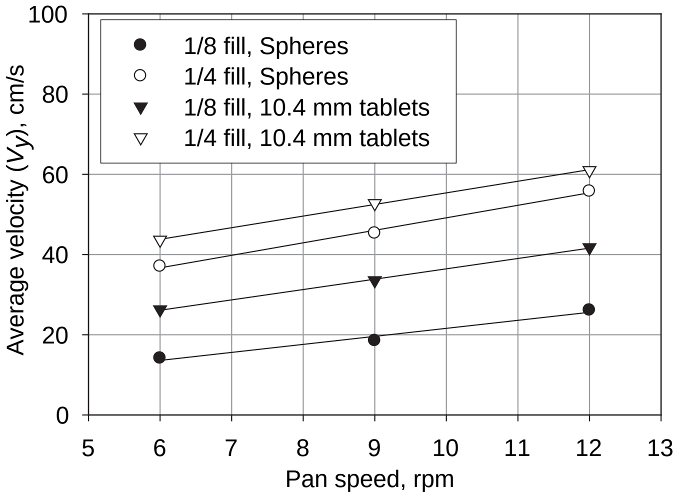

Figure 8. Comparison of average velocities in *y*-direction between spheres and tablets.

tively for one-eighth and one-fourth fill levels and were not significantly different from those observed for spheres. As noted previously, the dynamic angle was found to be significantly higher for tablets in comparison with spheres. This offers one possible explanation for the higher velocities of tablets. Another reason for higher tablet velocities is that the flowing layer is thinner for nonspherical particles than the spherical ones.[7] Thus, because of flux conservation, the free surface velocities of the nonspherical particles (tablets in this case), are higher. It was also noted that the shape of the cascading layer was much flatter for lower pan speeds and approached a more "wave-like" form at higher pan speeds. This is consistent with the findings of Yamane et al.[7] The wavy shape of the cascading layer was observed to be much more pronounced for tablets than spheres.

The dispersion coefficient (D_x) was evaluated using the x-direction displacement as described earlier and is plotted in Figure 9 for a 2-cm span on either side of the center of the cascading surface, with 9-mm spheres and 10.4-mm tablets at one-eighth pan fill. The D_x values for spheres were found to be much higher than those of tablets, indicating more axial movement occurring for spheres than tablet-shaped particles.

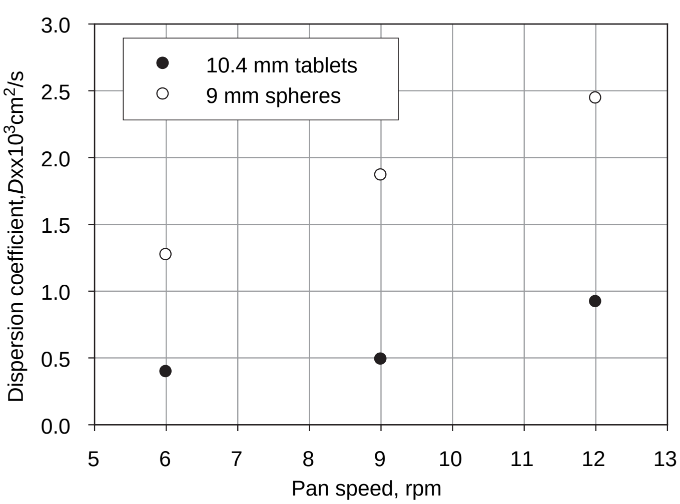

Figure 9. Comparison of dispersion coefficient (2-cm span) between 10.4-mm tablets and 9-mm spheres for one-eighth pan fill.

CONCLUSION

The velocity of particles in the cascading layer was found to increase with increasing pan speed and pan loading. A linear model was found to best describe the variation of particle velocity with pan speed. A significant difference in particle motion was observed between the standard round-shaped tablets and spherical particles with tablets moving faster than the spherical particles. The dynamic angle of repose was higher for tablets in comparison with spheres, and the bed surface was more wave-like in the case of tablets. The axial dispersion coefficient, D_x, was found to increase with increasing pan speed and was greater for spheres than tablets. Future studies are directed toward extending this work to an industrial scale pan-coating device.

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