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Blend Uniformity and Powder Phenomena Inside the Continuous Tumble Mixer Using DEM Simulations

Miguel Florian-Algarin and Rafael Méndez
Chemical Engineering Dept., University of Puerto Rico, Mayagüez, PR 00681

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Powder mixing is an essential operation in pharmaceutical, food, and petrochemical industries. Pharmaceutical companies have been working in the implementation of continuous processes as an alternative to the batch process using the food and drug administration process analytical technology initiative. The main goal was to understand the mixing phenomena inside the continuous tumble mixer and monitor blend uniformity using discrete element method. Results demonstrated that the main mixing mechanism is convection similar to the common tumbling mixers. This mechanism is driven by the bulk flow of the particles, due to the mixer rotation. The simulations' results, demonstrated that the cohesion reduces the concentration variability due to the higher holdup, particle interactions, and mean residence time. The blend uniformity at the exit of the system was measured and a relationship between relative standard distribution, cohesion, and the collision frequency was found. © 2014 American Institute of Chemical Engineers *AIChE J*, 61: 792–801, 2015
Keywords: pharmaceutical engineering, mixing uniformity, continuous mixing, residence time distribution, discrete element method, particle processing

Introduction

The use of discrete element method (DEM) to simulate and understand the behavior of granular materials has been increasing over the last years, primarily for batch systems. Granular mixing process is a major step in various industries including pharmaceutical companies. The process analytical technology is an initiative of the food and drug administration (FDA) to encourage the change from batch processes used in pharmaceutical companies to continuous processes. This initiative will be useful to improve process quality and to control instabilities during the different pharmaceutical operations, obtaining more efficient processes. Continuous mode has been applied in other industries such as chemistry, food, petrochemical, and cosmetics.[1–3]

Batch mixers

DEM has been used to study the particles behavior inside mixers or similar equipments to obtain a better understanding of these systems.[4–6] The computational capacity is an important factor to decrease the simulation time, and at the same time is a limiting factor. An option to decrease the simulation time is the use of two-dimensional (2-D) simulations. Xu et al.[4] used DEM to simulate a quasi 2-D experimental process demonstrating that density and particle size affect the final uniformity in the system studied and found a relationship between the rotation ratio and the flow regime obtained. Chaudhuri et al.[6] used the DEM to study the effect of cohesion in the mixing process by comparison of the simulation results with experimental images of a similar system. The results obtained showed that the mixing is influenced by material cohesion; high cohesion values produce slow mixing, and low particle cohesion produce a faster mixing. This effect is easy to visualize and has been showed in diverse studies.[5,7] The dynamics of particles in the system was studied by Alexander et al.[5] by coupling experiments and simulation results using three different cohesions: dry glass beads, pearls wet dry, and "dry" cohesive powders showing that in both cases cohesion affects the avalanche phenomenon and behavior within the mixer.

Continuous powder mixing

DEM has been used to study the mixing process in a continuous paddle mixer. Sarkar and Wassgren[8] simulated a periodic section of a continuous mixer to study the influence of the fill level and impeller rotation rate. The principal results showed that the combination between small fill and large impeller speeds produced higher dispersion, resulting in a better mixing homogeneity; and small fill with small impeller rotation produced a poor mixing.

Similar to mixing processes in batch mode, cohesion affects the continuous process and the effects have been studied experimentally and using simulations. Dubey et al.[9] used DEM simulations to study the powder behavior using two different strategies: first the entire blender (Gericke GCM250) and second a periodic slice of the entire blender in which they studied the impact of the impeller speed, fill level, and cohesion on the mixing performance and residence time distribution (RTD). Sarkar

Correspondence concerning this article should be addressed to R. Mendez at rafael.mendez1@upr.edu.

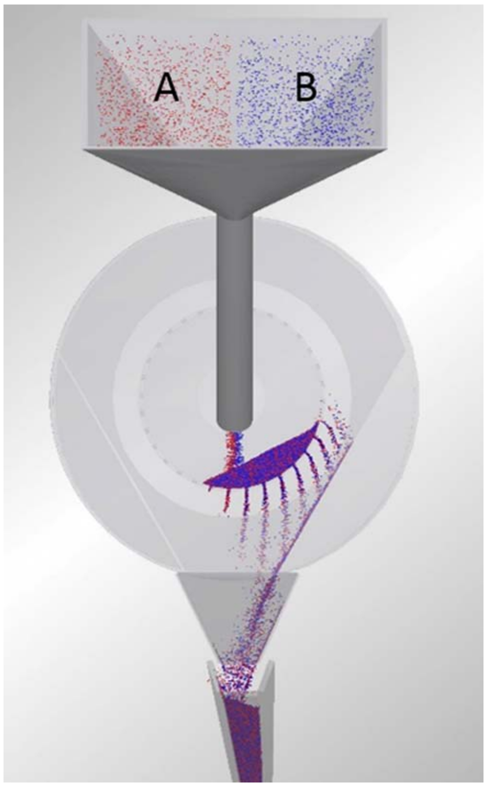

Figure 1. Schematic system used in the simulations.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

and Wassgren[10] presented the influence of the interparticle cohesion at various impeller speeds and different fill levels, demonstrating that the cohesion affects principally the axial mixing and the mixing performance for highly cohesive materials.

Gao et al.[11] proposed a periodic section model for continuous mixing based on the idea that this convective process is a combination of a batch-like mixing and an axial particle flow. Using DEM simulations and three different particle sizes (2, 3, and 4 mm), the authors investigated two study cases: nonsegregating mixture and a case with segregation effect. They found different relationships that could be used to design and optimize continuous mixing processes. A second part of this work was performed based on the previous results. The operating conditions and their influence on axial velocity (V_x) and local mixing rate (K_b) of the mixture demonstrated that the particles move faster and reside a shorter time inside the mixer at higher rotary speeds and lower fill levels.[12]

The goals of this work were to understand the effect of operating parameter and material properties on powder phenomena inside the continuous tumble mixer and mixing uniformity inside and at the exit of the system using DEM simulations. In addition, the velocity profile and the flow regime were validated experimentally. The mean residence time (MRT) was measured to determine the system response and measure the time available for particle interaction and mixing. This continuous mixer, unlike the common screw mixers, does not have paddles or impellers, reducing the shear impact on material properties. In addition, this mixer requires small operation areas and maintains the advantages of continuous operation.

Materials

Low shear continuous tumble mixer description

The simulated system was developed using Autocad® and has exactly the same dimensions of the real mixer. A detailed diagram of the geometry is shown in Figure 1 and a detailed description of the mixer can be found on our previous work.[13] This mixer has an internal diameter of 152.4 mm with multiple orifices in the radial wall. The materials used in these simulations are identified as particle 1 and particle 2 and represent active pharmaceutical ingredients (APIs) and the excipients used for the mixing process, respectively. Both particles enter the mixer by a tube using a flow of 0.009 kg/h for each particle. The mixer rotates counterclockwise making the particles slide or avalanche while exiting at the same time by the effect of centrifugal force. For these simulations, the velocities used were 50 and 70 RPM; these values were selected based on experimental results.[13]

Glass beads

To validate the simulations, mixing experiments were performed using the existent system[13] and 1-mm spherical glass beads. Velocity profiles and flow regimes were analyzed to compare these results with the simulation data obtained and to demonstrate that the behavior is similar for both cases.

DEM simulation software®

A set of simulations was used to study the phenomena occurring inside the mixer and to obtain a better understanding of the mixing process using DEM software®. This software is based on the DEM which is a powerful tool to simulate particulate systems.[4,14,15] DEM software uses Newton's law[16–18] to describe the motion of each particle (Eqs. 1 and 2) and the interaction between particles based on the initial particle characteristics

$$m_i \frac{dv_i}{dt} = \Sigma_j \left(F_{ij}^N + F_{ij}^T \right) + m_i g \qquad (1)$$

$$I_i \frac{dw_i}{dt} = \Sigma_j \left(R_i * F_{ij}^T \right) + \tau_{rij} \qquad (2)$$

In the previous equations, m_i, R_i, I_i, v_i, and w_i represent the mass, radius, moment of inertia, linear velocity, and angular velocity of particle, respectively, and the acceleration by gravity is represented by g. Using the information provided by this method, we can obtain velocity, position, and interaction forces for each particle. Simulations were performed using the no-slip Hertz-Mindlin contact model (Eq. 3), which is the default model included in the software program and is used to solve the particle–particle interaction[19–21]

$$F_n = -k_n \delta_n + C_n v_n^{\text{rel}} \qquad (3)$$

In Eq. 3, the terms k_n, C_n, δ_n, and v_n^{rel} represent spring stiffness constant, damping coefficient, the normal overlap, and the normal component of the relative velocity.

Methodology

As can be seen in Figure 1, a schematic model based on the real system was used to simulate the mixing process. The system includes the mixer and two factories where

Table 1. Simulation Parameters and Reference Values

Simulation Parameters	Used Values	Reference Values
Poison radius	0.5	0.25–0.3[12,22–24]
Shear modulus (Pa)	2.00 E +06	2.00 E + 06–3.00 E +08[22,23]
Coefficient of restitution	0.05	0.5–0.9[8,12,22–25]
Coefficient of static friction	0.5	0.3–0.5[8,12,23]
Coefficient of rolling friction	0.005	0.001–0.005[8,12,23–25]
Generation rate (Kg/s)	0.018	–

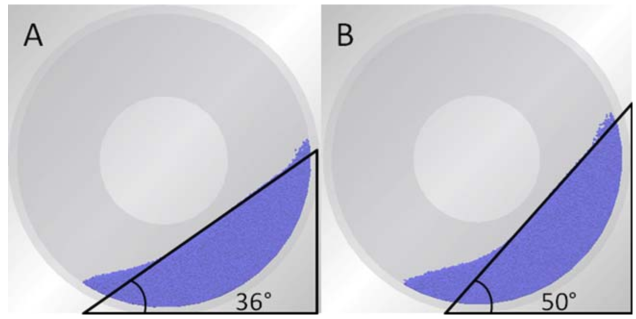

Figure 2. Batch mixer using cohesion 0 (A) and 2 (B) at 70 RPM.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

particles 1 and 2 are produced. These factories have the function of the feeders in the experimental part.

In this mixing process, the incoming materials interact with the powder that is already in the system. Points A and B in Figure 1 represent particles generation using a flow of 0.009 Kg/h of particles 1 and 2 which are identified with colors red and blue, respectively. Particle generations are placed on top of the system and these positions agree with the manner in which particles are fed on the experimental system. The design of experiments (DOE) includes mixer speed (50 and 70 RPM), and four different values were selected for the cohesion energy density. Other simulation parameters and the particle characteristics used in these simulations are shown in Tables 1 and 2, respectively.

The cohesion equation included in DEM software® used to add this property to the particles was obtained using the linear cohesion model (Eq. 4), where A is the contact area (m^2) and k represents the cohesion energy density (J/m^3). This model is a modification of the default Hertz-Mindling contact model for particle interactions and for particle geometry adding a normal cohesion force

$$F = kA \tag{4}$$

To select the values of the cohesion energy density, a batch tumble mixer was simulated using different values until change on powder behavior was observed. Figure 2 shows the results for simulations without cohesion and cohesion 2 at 50 RPM. An increment on the angle formed by the powder bed before sliding or avalanching was observed. This change affects the powder flow behavior and is caused due to the particle–particle and particle-wall cohesion. Based on this result, a higher cohesion value was added to the simulations' DOE to obtain a better understanding of the cohesion effect on powder flow phenomena and mixing performance. The complete DOE includes four different cohesion values; at 70 RPM, 0, 10,000, 20,000, and 30,000 J/m^3 that were used as the cohesion energy density. At 50 RPM, the highest cohesion value caused an overflow. The material drops through the feeding side of the mixer to the powder-collecting zone inside the system, affecting blend uniformity and reducing the range of system operability at 0.018 kg/s. A similar behavior was found in the experimental part[13] where the use of highly cohesive materials produced overflow inside the system at a certain flow rate. To avoid this effect and keep the flow rate constant, the value of 30,000 J/m^3 was changed to 25,000 J/m^3 (50 RPM simulation). For the cohesions mentioned earlier, the results do not demonstrated the presence of agglomerates or clumps. From now on, to identify the simulations (Table 2), these will be referenced with the mixer RPM (50 or 70) and the cohesion value (0, 1, 2, or 3). For all the simulations, the particle–particle interaction is two times the particle-wall interaction.

Concentration at the end of the system, mass holdup inside the mixer, RTD, mixing uniformity inside the system, exits effect on final concentration, flow regimes, and velocity profiles were analyzed for the whole simulation set.

Table 2. Particle Characteristics

Particle Characteristics				
Mass (g)	0.00073			
Density (g/cm^3)	1.4			
Standard deviation	0.0			
Diameter (mm)	1.0			
Cohesion energy density	0	1	2	3
Cohesion particle-wall at 50 RPM (J/m^3)	0	5000	10,000	12,500
Cohesion particle-wall at 70 RPM (J/m^3)	0	5000	10,000	15,000
Cohesion particle–particle at 50 RPM (J/m^3)	0	10,000	20,000	25,000
Cohesion particle–particle at 70 RPM (J/m^3)	0	10,000	20,000	30,000

Results and Discussion

To measure the quantity and concentration of particles, volume selections were created in different places of the system. Holdup and mixing uniformity at the exit, tumble exits, and inside the mixer were calculated using these volumes. DEM software® provides the quantity of particles 1 and 2 in each selection. Using these values, the concentration was calculated. Particles shared or overlapping two or more cells or volume selections only are counted one time, based on the position of its center of mass. Other methods such as point approximated method (PAM) and discrete particle method (DPM) use different forms to approach the effect of particles divided in different cells. PAM omits the particle shape replacing it by a point, which as in our case neglects the split of particles between the cells. Conversely, an analytical method based on DPM was developed in order to take into account the fraction of a particle that

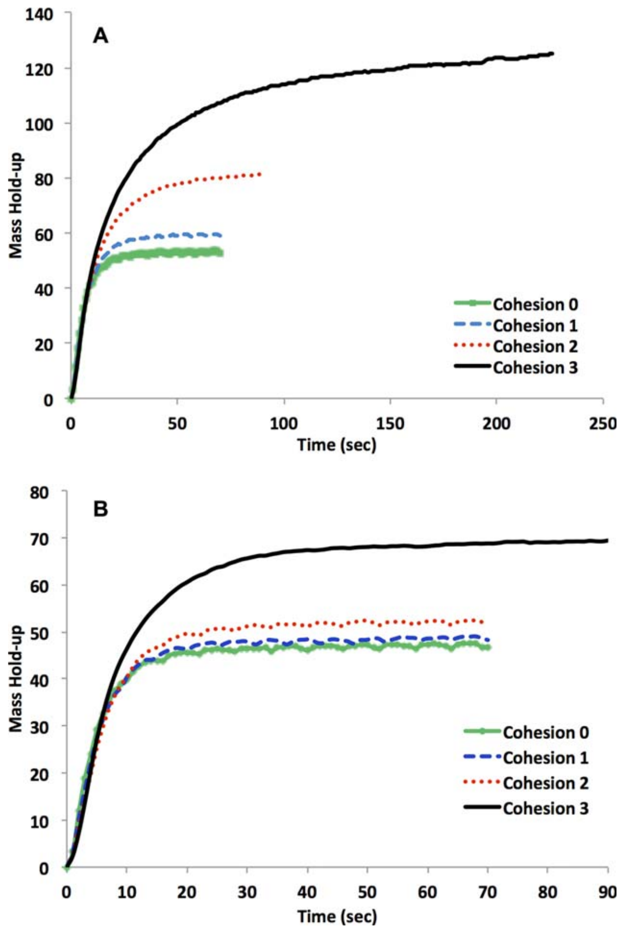

Figure 3. Mass holdup accumulation at (A) 50 RPM and (B) 70 RPM.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

belongs to each cell in the accurate calculation of void fraction.[26]

Holdup

Material holdup is an important variable in continuous processes related to mixer speed and flow rate.[1] The holdup was obtained from the total particle mass of a volume selection inside the tumble. Figure 3 depicts changes in mass holdup as a function of time until the mixer reaches mass steady state. At 50 RPM, for the simulations with cohesion 0 and 1, the time needed to achieve the steady state was similar and close to 30 s, for a cohesion slightly higher (cohesion 2) the steady-state time increases by more than two times, and for the highest cohesion time increases by six times relative to cohesion 0. At the highest RPM (70), the effect of cohesion energy density on the steady-state time was smaller, and the results showed practically the same time for cohesion 0, 1, and 2 and only showed a significant effect on steady-state time for cohesion 3 and were comparable to the value at 50 RPM for cohesion 2. These results indicated a higher effect of normal and centrifugal forces due to the increment in rotational velocity, which reduces the effect of the cohesion energy density. A higher cohesion value was required to promote a change in powder flow regime.

Table 3. Cohesion Effect on Mass Holdup and MRT

	Mass Holdup (g)		MRT	
Cohesion	50 RPM	70 RPM	50 RPM	70 RPM
0	52.64	46.66	4.10	4.03
1	58.91	48.27	4.30	4.26
2	81.27	52.18	7.83	5.13
3	123.66	69.34	9.94	7.95

Summarizing the results in Table 3, it is possible to observe that for a given mixer speed, larger cohesion values require larger accumulation of material to achieve steady state. The results showed an increment in the accumulation at constant feed rate when the mixer speed decreases and the cohesion values increases. This is an effect of the reduction in material flowability through the mixer exits due to particle–particle interaction caused by the cohesion.

MRT distribution

The RTD (Eq. 5) and the MRT (Eq. 6) are responses from the system that can be affected by the holdup and the flow regime and were used to quantify the time that the particles remained inside the mixer. To quantify this, a concentration of a tracer was tracked along time at the exit of the system using the age distribution function $E(t)$. It characterizes how much time various particles spend at the mixer[27]

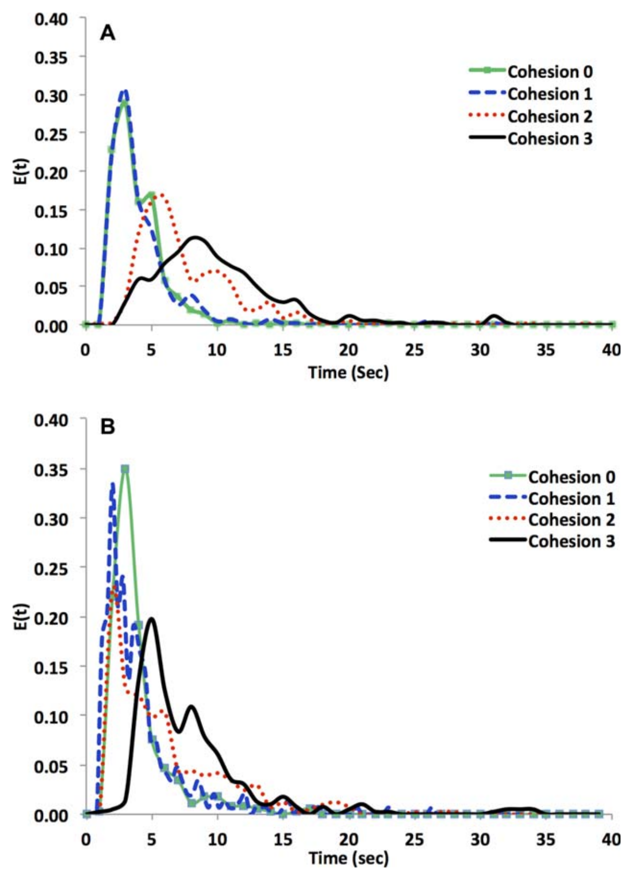

Figure 4. Residence time distribution at (A) 50 RPM and (B) 70 RPM.

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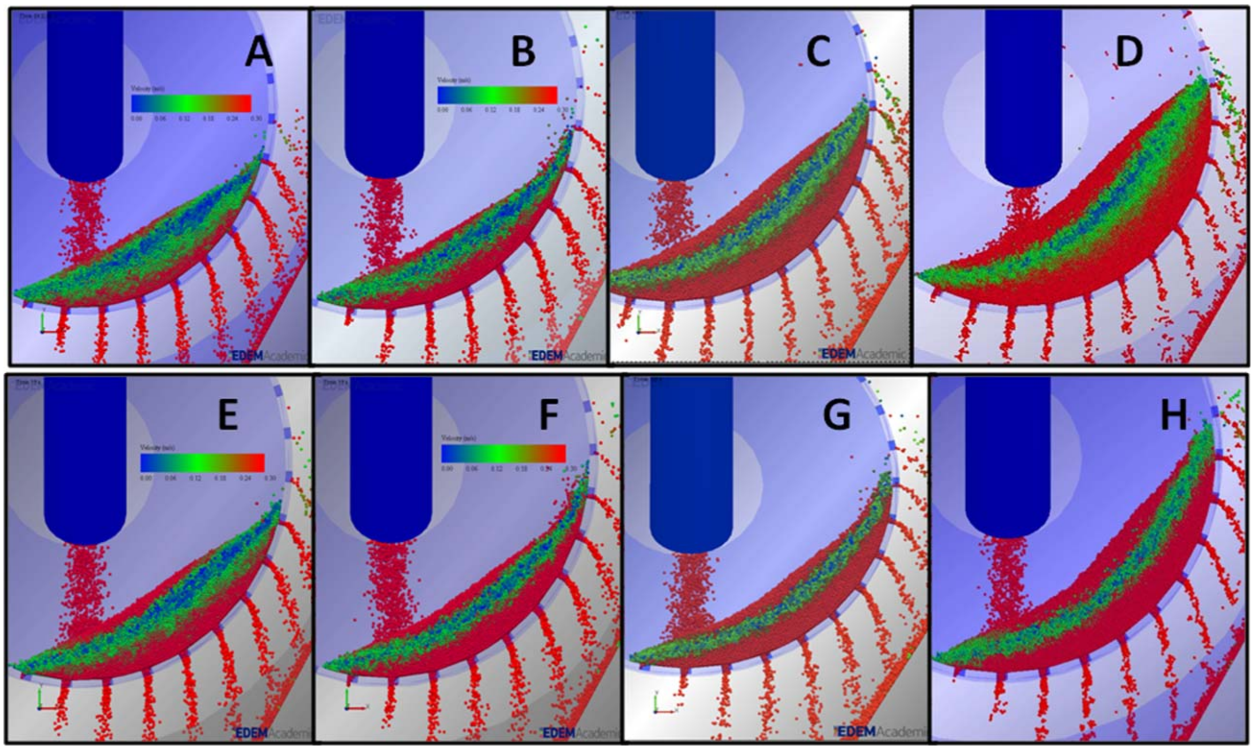

Figure 5. Velocity profile at 50 RPM, with cohesion 0 (A), cohesion 1 (B), cohesion 2 (C), and cohesion 3 (D), and at 70 RPM with cohesion 0 (E), cohesion 1 (F), cohesion 2 (G), and cohesion 3 (H).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

$$E(t)=\frac{C(t)}{\int_0^{\infty} C(t)} \quad (5)$$

$$\mathrm{MRT}=\int_0^{\infty} tE(t) \quad (6)$$

The residence time was measured using approximately 300 particles as a tracer during the mixing process. The tracer concentration was measured in 1 s intervals as the mixer reached the mass steady state. Results in Figure 4A illustrate the effect of the material cohesion on the age distribution function at 50 RPM. The results show a similar RTD for cohesions 0 and 1. For the simulation with cohesion 3, the age distribution depicts a wider and symmetrical distribution related to better dispersion of the tracer in the powder bed inside the mixer. Figure 4B shows a more narrow distribution at cohesion 0 compared to the distribution at 50 RPM that is consistent to a lower RTD. For the highest cohesion at 70 RPM and cohesion 2 at 50 RPM, the RTDs are similar indicating that the mixer speed reduced the cohesion effect on the RTD which caused the tracer to take less time to leave the mixer.

The MRT was calculated using Eq. 6, and the highest values were found for the simulations with the highest cohesion and these results were close to 10 and 8 s for 50 and 70 RPM, respectively. The MRT values were affected principally by the mixer speed and the particle cohesion.

Velocity profile and powder phenomena

The powder phenomena inside the mixer were initially characterized using the velocity profile after the mixer reached the mass steady state (feed rate equal to the exit flow rate). Results for the velocity profile at 50 and 70 RPM are shown in Figure 5 where we can observe the effect of the rotational velocity and the cohesion in holdup, powder phenomena inside the mixer, the particles movement, and the size of the active layer and the stagnant zone. Cohesion energy density affects the material flow behavior inside the tumbling mixer[6] and represents in certain manner the addition of a cohesive API to the experiments. This effect was more noticeable for the simulations at 50 RPM.

The colors in Figure 5 represent the velocity of the particles; red particles have the highest velocity (0.20–0.30 m/s), followed by the green particles (0.04–0.20 m/s), and the blue ones that are the slowest particles inside the system (0–0.04 m/s). The materials moving inside the mixer were divided in three regions, the top of the powder bed was the active layer, particles in the center correspond to the stagnant zone, and particles near the mixer wall were the recirculation zone. Focusing on Figure 5A, the active layer included a combination of green particle when the particle starts falling down in the active zone, followed by a small amount of red particles relative to the other velocity profile at larger cohesion. The behavior changed as the cohesion energy density increased in Figures 5C, D in which practically all the particles in the active layer are red (highest velocity). In addition, the size of the active layer increased due to the cohesion effect on mass holdup and flow behavior. The bottom of Figure 5 corresponds to 70 RPM and it is possible to observe a similar trend, with less variability in flow behavior compared to 50 RPM, indicating that the changes in flow behavior were more susceptible to the changes in holdup. These results show less slow particles and a higher number of faster particles for the simulations with cohesion obtaining an increment on the thickness of the active layer, which is

Figure 6. Simulation and validation using lactose and glass beads at 70 RPM.

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the layer where most of the mixing takes place.[28] The highest velocity particles close to the exits represent the recirculation zone and the amount of particles in this area is directly proportional to the holdup and causes a higher frequency of particle–particle interactions and higher MRT values.

To validate the velocity profile of the simulations, a set of experiments with the same operational parameters and similar particle characteristics, except the restitution coefficient, were developed. Glass beads of 1 mm diameter were used to validate the simulation without cohesion (Figure 6).

As can be seen in Figure 6, the results for 70 RPM show similar velocity profiles in the simulation without cohesion and the experiment with the glass beads. It is possible to identify the stagnant and the active layer based on the velocity profile and the resolution of the glass beads in the picture. The major difference occurs at the start and end of the sliding zone due to the higher restitution value of the glass beads compared to the simulation particles. The powder regime was characterized using the avalanche shape and the velocity profile. For the simulations, the flow regime corresponds principally to rolling regime; these results were different compared to the experimental part[13] in which the cascading and cataracting regimes dominate the flow behavior. Possible explanations are related to the particle size and the cohesion model used in the simulation, which only includes the contact effect between the particles and the particles and the wall. Based on the results in Figure 6, the values of the cohesion energy density used in the simulations do not completely represent the real cohesive material.

Using the velocity profiles, images, and simulation videos, it was possible to conclude that the particle trajectory and the powder phenomena inside the continuous mixer is similar to the behavior observed in batch tumble mixers. The flow regimes were classified as rolling, except for the simulation at 50 RPM with cohesion 3, which is in a transition to cascading.[29] This regime provides a higher mixing uniformity and is characterized by the presence of a flat surface, where it is possible to identify two regions: the active and the inactive layer. The particles movement in the active layer produces a powder dilation improving mixing performance. Also, the mechanisms occurring inside the mixer are similar to the mechanisms of the batch tumbling mixers previously reported on the literature. For these mixers, the mixing is generally based on convection in the particle flow direction. Diffusive mixing is considered relatively small compared to convective mixing mechanisms,[29,30] because this only occurs when there are displacements between particles in the two principal layers (active and inactive). The analysis of the simulations validated the existence of the two well-defined layers where particles remained before leaving the mixer.

Mixing uniformity

Mixing homogeneity is the principal response of the system and depends on all the parameters and variables discussed earlier. Based on Figure 1, it is possible to quantify the blend uniformity at the exit of the system, after the chute used to collect the powder of each exit point in one stream. In this section, the blend uniformity was analyzed in each mixer exit point and inside the mixer to understand the effect of powder phenomena on powder uniformity at the exits of the mixer and to elucidate if the design of the chute affects the final blend homogeneity.

Mixing uniformity at the exit of the system

For the simulations, a volume selection (Figure 7) was created after the chute to measure the quantity of particles 1 and 2 at the exit of the simulation system. The sample size was equal to 1 g of particles, and the concentration was calculated every second. With these values, the mixing uniformity was calculated (Table 4) and plotted in Figure 8; the results for the simulation are shown in Figures 9 and 10. These two plots depict the concentration variability as a function of time after the system reached mass steady state. This variability and the deviation between the target concentration value and the calculated value are higher as cohesion

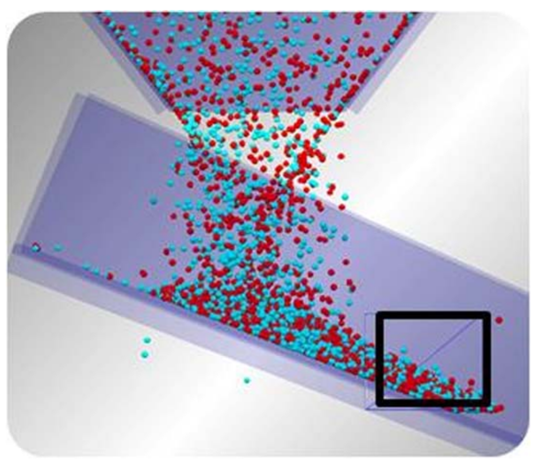

Figure 7. Sampling volume at system exit.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 4. Relative Standard Deviation

Cohesion	50 RPM	70 RPM
0	2.50	2.46
1	3.10	2.51
2	3.55	2.79
3	2.63	3.28

increases, except for the simulation at 50 RPM with cohesion 3, in which the deviation decreases relative to the target concentration value. The relative standard distribution (RSD) is the parameter used to measure the mixing uniformity and according to the FDA regulations for batch mixing processes, 6% values are considered to marginally pass and those below 4% are considered to really pass.[31]

The results were summarized in Table 4, and Figure 8 shows a good mixing with RSD values below 4%. These results demonstrated an increment in the RSD values as the cohesion energy density increases and the velocity decreases, except for the simulation at 50 RPM with cohesion 3. The lowest RSD was obtained for the simulation using 70 RPM without cohesion; at this rotational velocity, the RSD values are similar to the results for slightly cohesive particles (cohesion 2 or lower) found at 50 RPM. These results indicate a better mixing capability of the system for slightly cohesive material at higher velocity and are in agreement with the velocity profile analysis at 70 RPM in which a larger active zone and faster moving particles improve mixing performance. This trend validates the experimental results[13] in which a high mixing degree for the blends with 10 and 20% of API were found as the rotational velocity increases.

Collision frequency effect on the final uniformity

The previous mixing uniformity results showed that the concentration variability decreases when the mixer speed increases. The results also show that the RSD increases with the cohesion, except for the simulation at 50 RPM and cohesion 3 in which RSD value was lower than the RSD for cohesions 1 and 2. To explain this behavior, the collision frequency inside the mixer for each simulation was calculated (Figure 11). An increment of approximately 20% in the collision frequency relative to cohesion 0 was obtained for the simulation at 50 RPM and cohesion 3 using DEM software©. This parameter has previously been related to the mixing uniformity.[18] The increase in the collision frequency is explained for the change in powder phenomena inside the mixer showed in Figure 5D; using this figure, it is possible

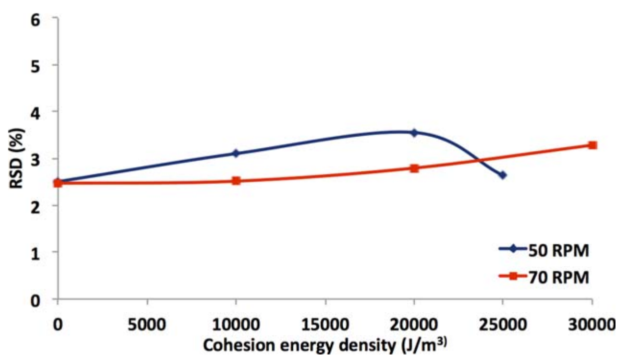

Figure 8. Effect of cohesion on final blend uniformity.

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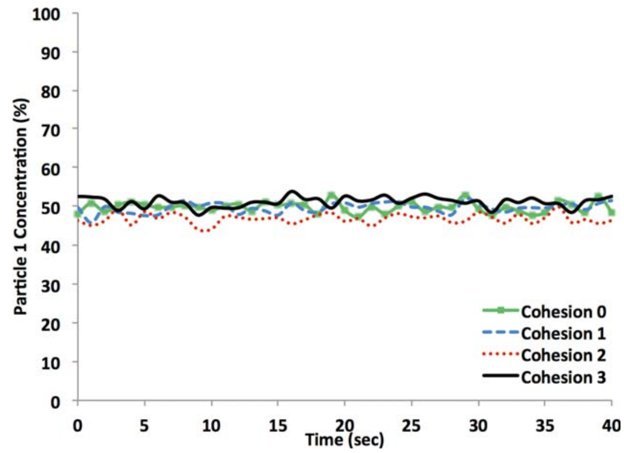

Figure 9. Mixing uniformity after the mixer reached the steady state at 50 RPM.

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to observe that the number of particles moving faster increases compared to the other simulations.

Mixing uniformity at the exit of the mixer

Using simulation videos, it was observed that the uniformity is the contribution of the material flowing by each exit and its interaction in the chute. To demonstrate the effects of the exit position on the final uniformity, the concentration was measured in each exit to compare it with the global concentration. To quantify the blend uniformity at the mixer exits, eight different volume selections (Figure 12) were created at the tumble exits to measure the differences in concentration between each one and its contribution on the final blend uniformity.

Measuring the concentration in each exit helps to understand the mixing dynamics inside the continuous tumble mixer. The results on Figure 13 show a concentration profile where the higher concentrations are in the exits closer to the feed inlet. The values obtained in exits 7 and 6 indicate the possibility of a shortcut in which particles are exiting the system without interacting with the material that is already inside, due to the recirculation zone. The higher deviations

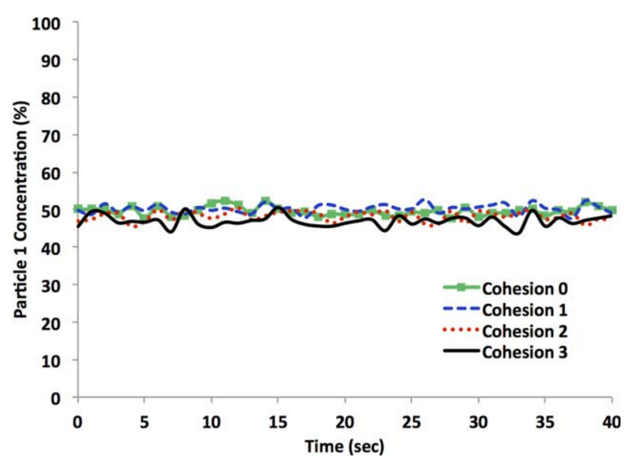

Figure 10. Mixing uniformity after the mixer reached the steady state at 70 RPM.

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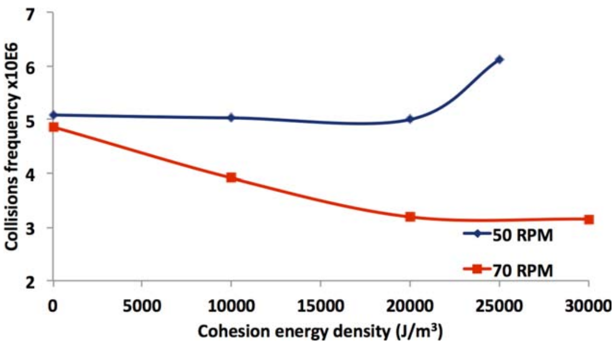

Figure 11. Effect of cohesion parameter on collision frequency.

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in the positions closer to the feeding position at 50 RPM were lower at 70 RPM and indicated that the higher velocity in the recirculation zone reduces the particle shortcut. When the cohesion was added (Figure 14), an inverse relationship was found between the cohesion and particle deviation in positions 7 and 6. For cohesions 2 and 3, the concentration oscillates around the target concentration indicating a reduction on particle shortcut.

In general, the concentration in each exit depicts a concentration profile in which the highest values occur at the bottom and the lowest in the exit on the top of the powder bed. A reduction in the concentration deviation was observed as the material cohesion increased, producing a more uniform material leaving the mixer.

Mixing inside the system

Previous studies in a batch tumble mixers showed that the mixing occurs principally in the active layer.[29] Four different volume selections were developed inside the avalanche to study the mixing uniformity inside the system (Figure 12). Two volumes were selected in the active and inactive layer (stagnant layer) based on the particle velocity profile (Figure 5). Other two selections were created with the name of upper and bottom layer corresponding to the base and top of the slide or avalanche zone; these two zones were closer to exits with the higher concentration deviation.

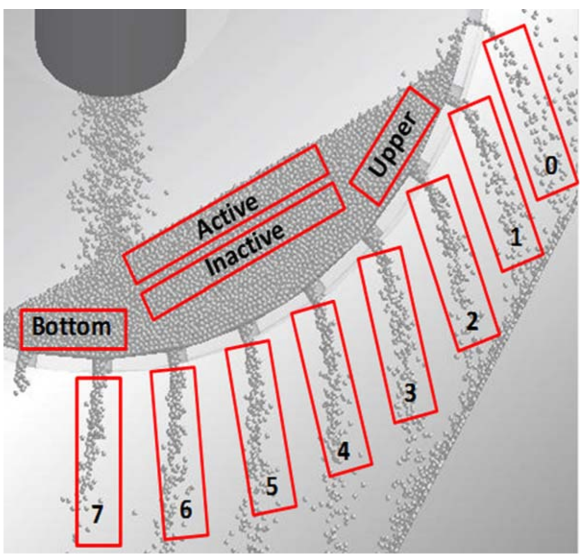

Figure 12. Sampling volumes inside and at tumble exits.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

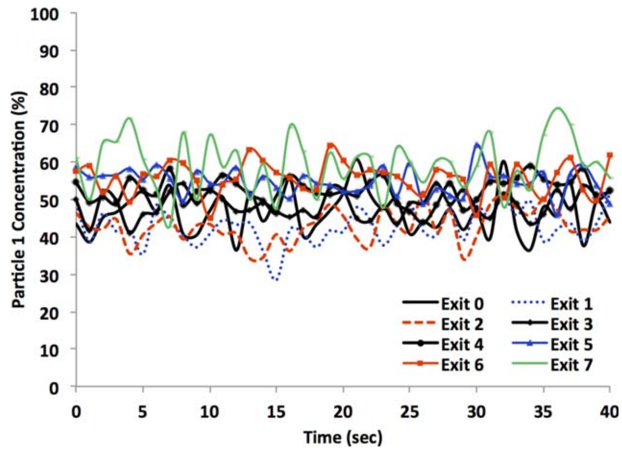

Figure 13. Exits effect on final concentration at 70 RPM cohesion 0.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The first volume was the active layer and the results show that the concentration values were oscillating around a concentration of 40% for noncohesive powder. For simulations at 50 RPM, the average concentration in the active zone is equal to 40.3 and 49.5% for cohesions 0 and 3, respectively. That shows a trend to achieve a closer concentration to the target value (50%) as cohesion increases. The second was the inactive layer (stagnant zone) with concentration values around 27.0 and 53.3% for cohesions 0 and 3, respectively. The upper concentration was 41.0 and 51.0 and the bottom was 43.5 and 51.8, respectively, for cohesions 0 and 3. The variability inside the system was plotted and is shown in Figure 15 (cohesion 0) and Figure 16 (cohesion 3) for the simulations at 50 RPM. These results show that the particle uniformity changes with the position inside the mixer, and this behavior was similar for all the simulations.

Summarizing, it was found that particle–particle and particle-wall interactions significantly reduce the shortcut,

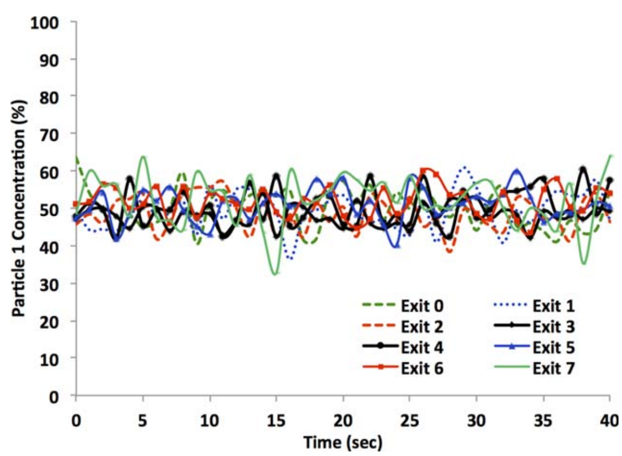

Figure 14. Exits effect on final concentration at 70 RPM and cohesion 3.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

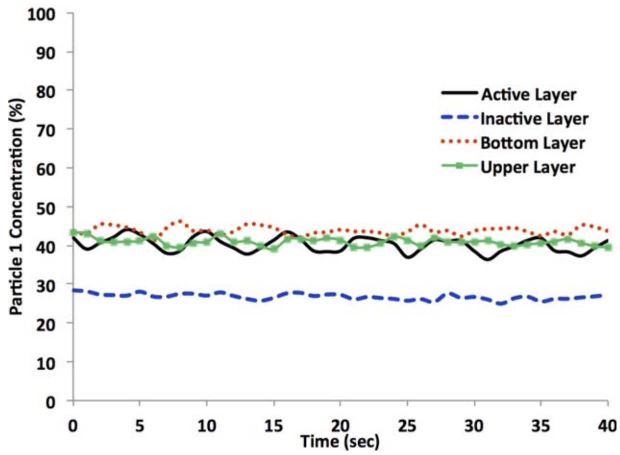

Figure 15. Mixing uniformity inside the system at 50 RPM and cohesion 0.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

and the concentration inside the mixer was closer to 50% for cohesions 2 and 3. Combining the results at the mixer exit points and inside the mixer, the addition of certain cohesion to the material promotes a better particle interaction and improves mixing uniformity.

Mixing uniformity comparison at the mixer exit points and after the chute

The use of DEM simulations demonstrated that this mixer is capable of achieving higher mixing uniformity and how the operation parameters and the material properties are related with the final blend homogeneity. The addition of cohesion to the simulations has a direct impact to the holdup increasing the particle interactions due to the higher particle velocity and the size of the recirculation zone. The combination of effects, the holdup, and the velocity profile promoted a higher MRT. These results were consistent with the experimental part in which the increase in material cohesion reduced the operation capability of the system at constant flow rate and constant mixer speed. In this case, it was required to increase the mixer speed or reduce the inlet flow rate.[13]

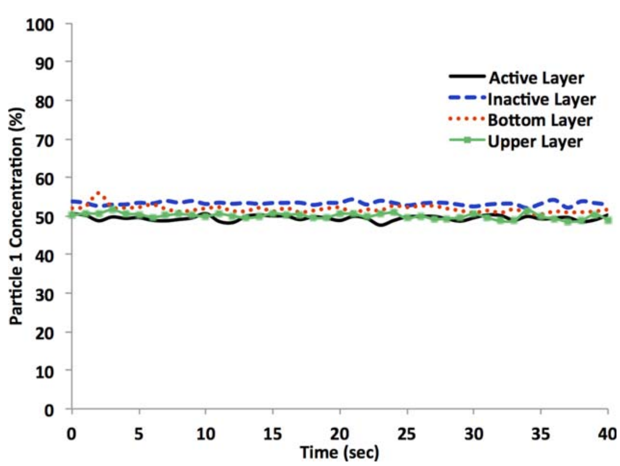

Figure 16. Mixing uniformity inside the system at 50 RPM and cohesion 3.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The blend uniformity at the exit of the system was characterized based on the parameters mentioned earlier and an increment in RSD with cohesion was found, except for the highest cohesion at 50 RPM in which a reduction in RSD was observed. This demonstrated that the cohesion negatively affects blend uniformity when the flow regime is rolling, and small changes in flow regime (to cascading) provide a significant increment in the collision frequency improving blend uniformity. This behavior was similar to the results obtained in the experimental part, in which a regime with higher particle–particle interaction (cascading or cataracting) was required to obtain good blend uniformity. The concentration was analyzed in each mixer exit point and inside the mixer to have a better understanding of the effect of powder phenomena on blend uniformity. The results in each exit point and inside the mixer demonstrated that cohesion reduces the concentration variability due to the higher holdup, particle interactions, and MRT. In addition, a closer concentration to the target value was found for both mixer speeds. Summarizing, these results are not consistent with the reduction in blend uniformity found at the exit of the system; except for cohesion 3 at 50 RPM. This disagreement could be related to the particle–particle interaction between material moving in the chute with the material leaving the mixer in each exit point (Figure 12) causing an additional mixing effect. For example at cohesion 0, the outgoing material in exits 6 and 7 with concentration higher than the target value (due to the shortcut) interacted with the material leaving the other exits, including the material with concentration below the target value.

In the future, more simulations will be performed to try to establish a correlation to predict the MRT as a function of the operating parameters (feed rate and mixer RPM) and powder properties such as cohesion. To estimate the mixing uniformity, it will be necessary to find an additional relationship between the MRT and the RSD.

Conclusions

Based on the previous results, we show that the continuous tumble mixer has the capacity to reach an optimal production with low concentration variability. The velocity profiles and the flow regime results demonstrated that the powder behaviors inside the mixer are similar to the batch system. These were validated using glass beads, showing a similar behavior based on the avalanche shape, powder phenomena, and the velocity profile inside the mixer.

The focus of this work is to understand the powder phenomena and determine the material uniformity at the exits of the system, in order to find a better blend uniformity for simulations at 70 RPM at low cohesion. For the case with the highest cohesion, the uniformity was a function of the mixer speed and the flow regime, in which the regime was the predominant effect increasing the cohesion frequency. The change in flow regime from rolling to cascading was a combination of the cohesion and the material accumulation inside the mixer (holdup) at constant mixer speed. The results demonstrated that the change of flow regime improved the blend uniformity.

Other important results showed a concentration profile at the exits of the tumble, with highest and lowest values at the exits closer to the bottom and top of the powder bed, respectively. In addition, a variability reduction inside the mixer and at the system exits was found when the cohesion values increased.

To improve the mixing performance, the shortcut effect (mentioned earlier) can be studied using a new feeding position to force the feeding material to fall on top of the active layer, reducing the possibility of it leaving the system without interacting with the material that is already inside the mixer.

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