Quantitative Characterization of Mixing of Dry Powders in V-Blenders

Dean Brone, Albert Alexander, and F. J. Muzzio
Dept. of Chemical and Biochemical Engineering, Rutgers University, Piscataway, NJ 08855

Experiments were conducted to determine the effect of rotation rate, fill level, and total number of revolutions on the mixing performance of a V-blender. The experiments were performed using 66- μm red and green glass beads. Mixture uniformity was quantified after each experiment by infiltrating the mixtures with a binder, and using image analysis to examine slices of the solidified mixture. The mixing rate (as a function of total revolutions) was not affected by changing the rotation rate between 8 and 24 rpm. The mixing rate increased significantly as the fill percentage was decreased from 60% to 40% of the total vessel volume. In a symmetric blender such as a V-blender, the rate of mixing is limited by the rate of mass transfer across the vessel plane of symmetry orthogonal to the axis of rotation. A one-parameter model based on the amount of material that crossed the plane of symmetry per revolution displayed good agreement with the experimental data.

Introduction

Mixing of granular materials plays an important role in many industries ranging from pharmaceuticals to ceramics and plastics. Mixer types can be divided into two main distinct categories: convective blenders and tumbling blenders [for a review of blender types, see Fan et al. (1972, 1990); Poux et al. (1991)]. While convective blenders involve the use of a paddle, blade, or screw to stir the powder inside an immobile vessel, tumbling blenders rely upon the action of gravity to cause the powder to cascade within a rotating vessel. Convective blenders exhibit variations in both blade and bowl geometries, while tumbling blenders differ mainly in the geometry of the vessel.

This article seeks to determine the role of various experimental parameters (rotation rate, fill level, mixing time) upon the performance of a V-blender. The V-blender (also known as twin-shell mixer or PK blender) is one of the tumbling mixers most commonly found in industry. It consists of two hollow cylindrical shells, usually joined at a 75–90° angle. The mixing vessel is connected to a rotating shaft, causing a tumbling motion of the powders as the vessel is rotated. It is used both in the laboratory as a small-scale product-development unit and in manufacturing as a large-scale production unit.

Most previous work has involved using the V-blender in a comparison of several mixer types (Harnby, 1967; Harwood et al., 1975; Adams and Baker, 1956; Gray, 1957; Lai and Hersey, 1981; Williams and Khan, 1973; Carstensen and Patel, 1977; Chowhan and Linn, 1979; Kaufman, 1962; Wiedenbaum, 1958) or as a vehicle for testing blender efficiency for various powder characteristics (Harnby, 1967; Harwood et al., 1975; Adams and Baker, 1956; Gray, 1957; Lai and Hersey, 1981; Williams and Khan, 1973; Carstensen and Patel, 1977; Chowhan and Linn, 1979; Kaufman, 1962; Wiedenbaum, 1958; Cahn et al., 1965; Chang et al., 1992, 1995; Samyn and Murthy, 1974). As such, there is little systematic data on V-blender performance for a single powder constituent under controlled conditions. The few studies that used the V-blender as the sole mixer, either looked at means to improve performance (by altering vessel geometry) (Cahn et al., 1965; Chang et al., 1992, 1995; Brone et al., 1997) or tested different powder types (Samyn and Murthy, 1974) rather than attempting to fully describe the mixing processes occurring within the V-blender vessel.

It is important to note that most previous work with V-blenders has used either thief sampling (Lai and Hersey, 1981; Carstensen and Patel, 1977; Chowhan and Linn, 1979; Kaufman, 1962; Widenbaum, 1958; Cahn et al., 1965; Samyn and Murthy, 1974) or sampling during/after mixer discharge (Harnby, 1967; Harwood et al., 1975; Chang et al., 1992, 1995) as the means for determining mixture composition. Thief sampling has been shown to be unreliable in a number of

Correspondence concerning this article should be addressed to F. J. Muzzio.

previous studies (Williams and Khan, 1973; Orr and Shotton, 1973; Schofield, 1976; Poole et al., 1964; Carley-Macauly and Donald, 1962; Gopinath and Vedaraman, 1982; Gayle et al., 1958; Masiuk, 1987; Berman and Planchard, 1995; Muzzio et al., 1997) and it only affords a limited amount of information about mixture properties. If mixing is characterized by sampling the mixture during discharge, it is impossible to determine whether the discharged samples are truly indicative of the mixture quality within the blender or if they are affected by mixing/demixing actions occurring during the discharge process itself.

In this study, a detailed characterization method is used to determine mixture composition *in situ* (i.e., inside the blender). The mixer contents are solidified, sliced, and the resulting slices of the undisturbed mixture are examined by image analysis. This approach precludes the inherent randomness and error associated with thief sampling and generates reliable and extensive measurements of the overall composition distribution of the mixer contents. We focus on one powder system and one blender geometry, and examine in some detail the effects of the three operational parameters that are most relevant to industrial operations: rotation rate, filling level, and mixing time. The mixing apparatus, experimental methods, and image analysis technique are discussed in the following section. Experimental results are presented in the third section. A simple model that efficiently describes the evolution of the composition variance is also introduced in the third section, and conclusions are presented in the fourth section.

Experimental

A custom-designed mixing apparatus was used to examine the effects of operating parameters on mixing processes inside a partially filled V-blender. Rotation was controlled using a stepping motor (Arrick Robotics, Hurst, TX) interfaced to a computer (Gateway 2000, North Sioux City, SD). A motor-control computer program capable of varying rotation speed during each experiment was developed to enable precise control of the motion of the mixing vessel. Since industrial V-blenders generally run at a single constant speed, the rotation rate was kept constant during a given experiment. Thus, each experiment was defined by a specified rotation rate, mixing time, and fill percent.

The experimental techniques used in this study have been described in detail elsewhere (Wightman et al., 1995; 1996; Brone et al., 1997); only a brief description is presented here. Custom-made disposable aluminum mixing vessels (American Aluminum Co., Mountainside, NJ) that were 76 mm in diameter, 153 mm long, and had a 90-degree angle between shells were used in all the experiments reported here. The total loading for each experiment was 40–60% of the total vessel volume. These filling levels correspond to the range of 60% to 100% of working capacity commonly used in industrial applications. The vessels were loaded axially with red and green 66-μm glass beads (Potters Industries Inc., Parsippany, NJ), with one color being loaded into each shell (Brone et al., 1997). The initial condition for each experiment is shown in Figure 1.

At the end of the mixing experiment, the structure of the mixture was preserved by infiltrating the blender contents

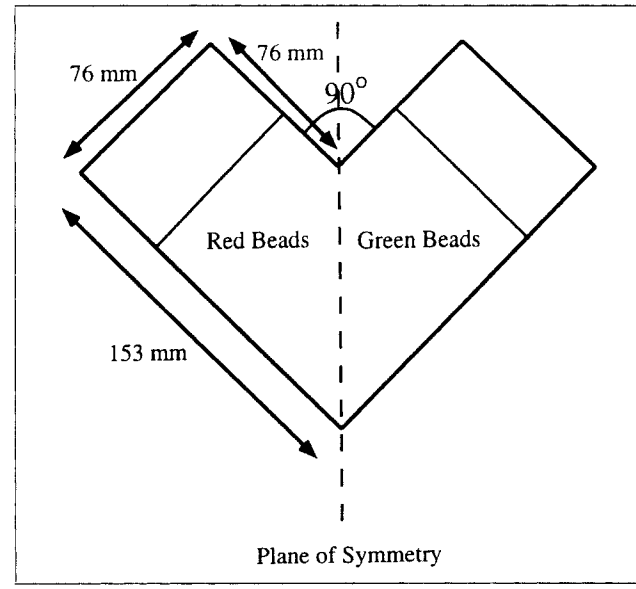

Figure 1. V-blender vessel showing the axial loading initial condition used in the experiments.

with a polymer solution (Rave, Chesebrough-Ponds USA Co., Greenwich, CT), which was allowed to cross-link, yielding a solidified monolith (Wightman et al., 1995). This monolith was subsequently cut into half-inch slices (Figure 2) to reveal the internal structure of the mixture. Repeated experiments that froze both horizontally and vertically layered structures showed that the infiltration process did not cause appreciable disturbances to the mixtures.

Quantitative mixing data were obtained from the slices by image analysis using equipment and procedures that have

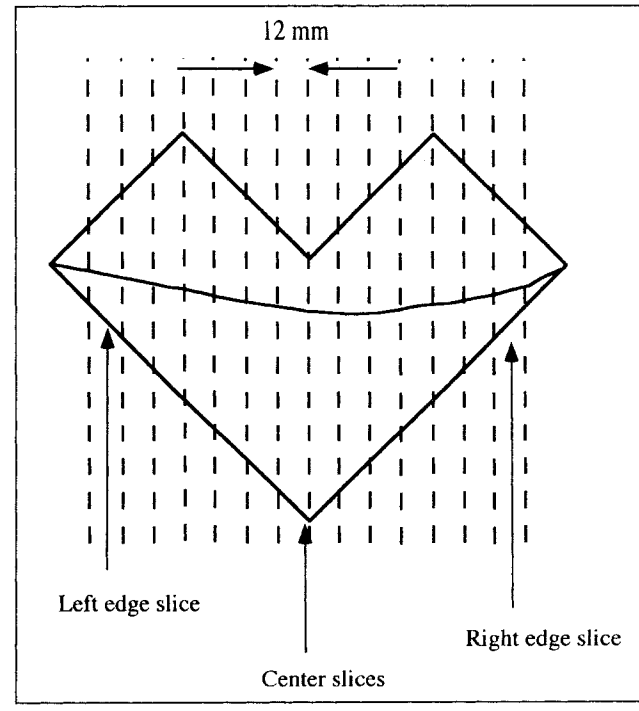

Figure 2. Slicing scheme for solidified experiments.

been described in detail in a previous publication (Wightman et al., 1996). Each slice was scanned using a video camera with the aid of a programmable xy-table (Unidex Aerotech Inc., Pittsburgh, PA) operated remotely by a computer. Image-processing software handled the video signal, data retrieval, and storage (Wightman et al., 1996). During image acquisition, a slice of the mixture was partitioned into separate fields of view, each 5 mm by 6.7 mm. Each field contained approximately 9,000 particles and was digitized into 480×512 pixels, with each pixel possessing a gray level on a scale from 0 to 255. A filter was used to maximize gray-scale contrast of the red and green components. During processing, each field of view was further subdivided into regularly spaced regions, called "patches." The local composition was measured for each of these small patches by computing the mean gray-level intensity of the pixels in the patch. Although averaging within patches "blurred" some of the image detail, the large number of patches used in the analysis (10^3 to 10^4 per slice) gave a detailed characterization of the composition statistics of the entire mixture. A typical slice is shown in Figure 3a, and the reconstructed image using the mean gray-scale value of the patches is shown in Figure 3b. The reconstructed image retains a large amount of detail found in the actual mixture, making it possible to perform a detailed characterization of mixture structure for each experiment.

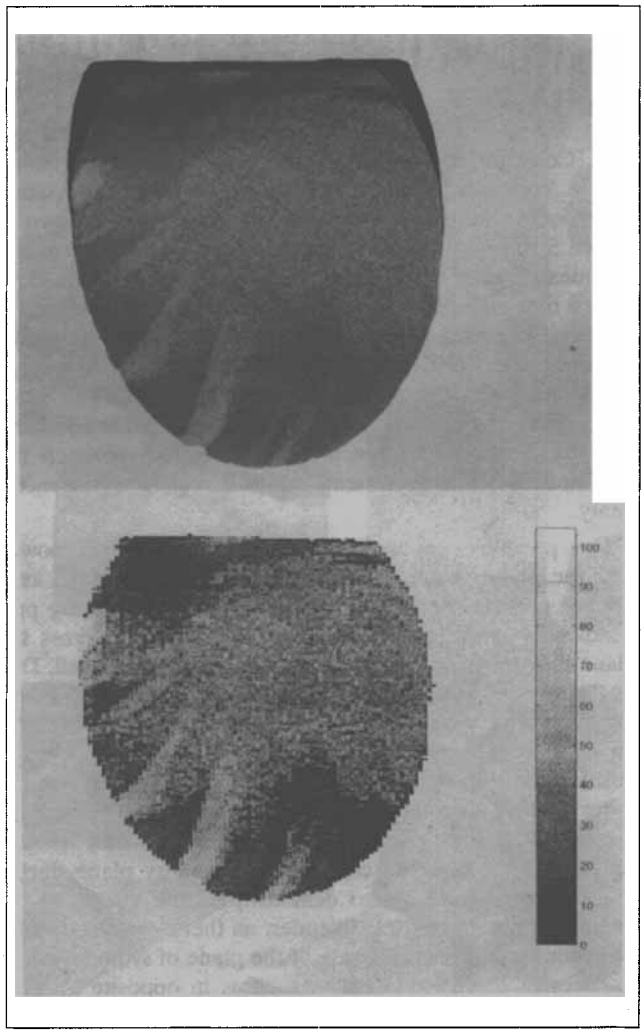

Figure 3. Data-acquisition sequence of the slice: (a) photograph; (b) digitized image.

Results and Discussion

The discrete nature of granular systems generates variability within the powder structure even in well-mixed systems. Samples of granular mixtures often contain a relatively small number of particles (compared to the billions of molecules usually encountered in gas and liquid samples). Because of this small scale of examination, composition variability never vanishes completely, and can often be significant, due to the intrinsic statistical variability of finite-size systems. A meaningful assessment of "mixedness" in such a system is performed by comparing the observed variability with the variability of a random mixture, which represents the best achievable mixing for a granular system. For a binary system composed of constituents differing only by color, the standard deviation of a random mixture, σ_R, is

$$\sigma_R = \sqrt{\frac{P_A P_B}{N_A P_A + N_B P_B}},$$

where P_i is the probability that a given particle will be component i, and N_i is the average number of particles in a pure sample of component i. For our analysis method, the sample size corresponds to one patch, which contains approximately 140 particles (as determined by counting particles on a picture obtained from scanning electron microscopy). Using $N_A = N_B = 140$ particles per sample and 50% concentration of particles of each color, the standard deviation of samples with a random composition is calculated to be 4.23%. In comparison, the image analysis system used in this study generated standard deviations ranging from 4% to 8% for mixtures that appeared homogeneous to the naked eye.

Previous studies (Kaufman, 1962; Carley-Macauly and Donald, 1962; Cahn et al., 1966; Donald and Roseman, 1962; Hogg et al., 1966; Henein et al., 1983; Hogg and Fuerstenau, 1972; Carley-Macauly and Donald, 1964) have demonstrated that several flow regimes can exist in a rotating cylinder, including slipping, slumping, rolling, cascading, cataracting, and centrifuging. The speed of the vessel relative to the critical speed required to centrifuge the particles determines which flow regime dominates. In fact, this is akin to classifying flow in terms of its Froude number ($Fr = V^2/gL$), where V is the characteristic speed (usually the tip speed) and L is the characteristic length (usually the vessel diameter). Three flow regimes (tumbling, partial-inertia, and centrifugal) were characterized for the V-blender used in this study, by observing the motion of 66-μm beads in a Plexiglas V-blender rotating at variable speeds. Particle motion was videotaped and replayed in slow motion in order to allow for easier identification of the flow characteristics. The first mode of particle motion was dominated by tumbling motion, characterized by particles cascading from one end of the shell to the other, with the mixture splitting and reforming during each rotation. A gradual transition to the second mode of particle motion began at about 70 rpm. In this regime, the mixer rotated too fast for all the particles to complete tumbling from one

end of the shell to the other. Since all particles did not reach the end of the shell, some became airborne as they fell from a position no longer supported by the vessel to another location that was supported. As the rotation rate increased, a gradual shift toward the third mode of particle motion occurred, which was totally dominated by particle inertia. In terms of Froude number, the conditions under which inertial effects become important correspond to $0.416 < Fr < 1.91$. At speeds of 150 rpm or greater ($Fr > 1.91$), the particles remained fixed at the ends of the shell and did not move relative to one another. All experiments for this study were performed between 8 and 24 rpm, corresponding to Froude numbers of 0.0058 to 0.057. Since these speeds are far below the transition to the partial-inertia regime, tumbling motion dominated in all of our experiments. This range of Fr also corresponds to conditions used in industrial applications, in which large-scale tumbling blenders are usually operated at $Fr < 0.2$. While only results for 66-μm particles are presented here, we wish to remark that the same three regimes were observed to occur at the same values of Fr when the experiments were repeated for 600-μm beads, suggesting that for the free-flowing particles considered in our experiments the flow regimes are independent of particle size.

The effect of rotation rate on the evolution of the standard deviation of mixtures is illustrated in Figure 4 for 40% fill. This value corresponds to 66% of working capacity. The nature of the freezing/slicing quantification technique requires sacrificing the mixture in order to perform image analysis. Thus, in curves such as those shown in Figure 4, each data point corresponds to a separate experiment. In order to minimize the effects of environmental variables such as temperature and humidity, which affect the flow of granular materials, all experiments within a curve were performed over an interval of a few days under similar environmental conditions. In Figure 4, results are compared for 8, 16, and 24 rpm. The data demonstrate that in this regime, rotation rate exerts little influence on the mixing process; in all cases, the evolution of the standard deviation is independent of rotation rate and can be expressed solely as a function of the total number of revolutions (which is the properly nondimensionalized mixing time). Starting from the upright position, the flow splits the mixture in the first half revolution. Once particles reach the wall on the opposite end of the blender, they move as a solid body until the configuration of the vessel with respect to gravity is changed enough to cause the particles to tumble back to the other end of the blender, reassembling the mixture. Qualitative observations indicate that this tumbling motion, which is gravity driven, is largely independent of the rotation rate for low enough Fr numbers. Particles *within one shell* are mixed relatively quickly by convective rearrangement during the tumbling motion. Mixing between shells occurs more slowly, as particles cross from one shell to the other only as the mixture is reassembled. Hence, the important factor determining the overall extent of mixing is the total number of times the mixture splits and reforms, rather than the rotation rate. In terms of total mixing time, however, the rotation rate is very important, because tripling the rotation rate from 8 to 24 rpm produces a uniform mixture three times as fast.

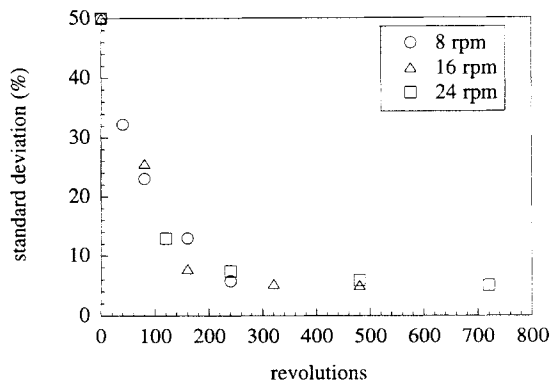

Figure 4. Effect of rotation rate on mixing rate.

The standard deviation is shown as a function of number of revolutions at 40% fill.

The effects of fill percentage for experiments run at 16 rpm for 20 min are shown qualitatively in Figure 5. Figure 5a shows an experiment run at 16 rpm for 20 min with a 40% fill (66% of working capacity). The color difference between the two halves is barely distinguishable, with an overall standard deviation of 6%. (All standard deviations reported in this article are absolute standard deviations in terms of composition percent. In cases where there is an uneven number of slices, the center slice is omitted and the same number of slices from each half of the blender are analyzed). Increased heterogeneity is seen in Figure 5b, which shows an experiment run with a 50% fill. The difference in color between the two halves is now noticeable, and corresponds to a standard deviation of 8%. For 60% fill, heterogeneity increases even further. Color differences between the shells are apparent in Figure 5c, which shows a mixture with a standard deviation of 18%. The differences between the experiments shown in Figure 5 can be further clarified by quantitatively examining the mean compositions of each slice, which are plotted in Figure 6 as a function of the slice position along the axis of rotation. The data show a clear trend, confirming the observations made for Figure 5a–5c. A flat curve, indicating a nearly homogeneous mixture, is obtained for 40% fill, while increasingly nonuniform profiles are obtained for 50% and 60% fill. It should be noted that the overlap between the 50% and 60% fill experiments is within experimental uncertainty.

In a previous communication, Brone et al. (1997) showed that the main barrier to mixing in a V-blender is the axial flow of particles across the vertical plane of symmetry perpendicular to the axis of rotation; once particles cross the plane they are mixed relatively quickly within each shell. Due to the symmetric design of the V-blender, there is no inherent convective mechanism for the particles to cross the center of the vessel. As the V-blender rotates from an inverted position to an upright position, the particles converge to the lower end of the vessel, reaching the plane of symmetry at the center of the vessel at the same time, so only a small fraction of the material crosses the symmetry plane during this process. Figure 6 also demonstrates the effects of the symmetric design of the V-blender, as there is a nearly constant composition on each side of the plane of symmetry. Differences in composition between slices in opposite shells is much greater than differences between slices within a given shell, demonstrating that mixing within a shell occurs much more quickly than mixing between shells.

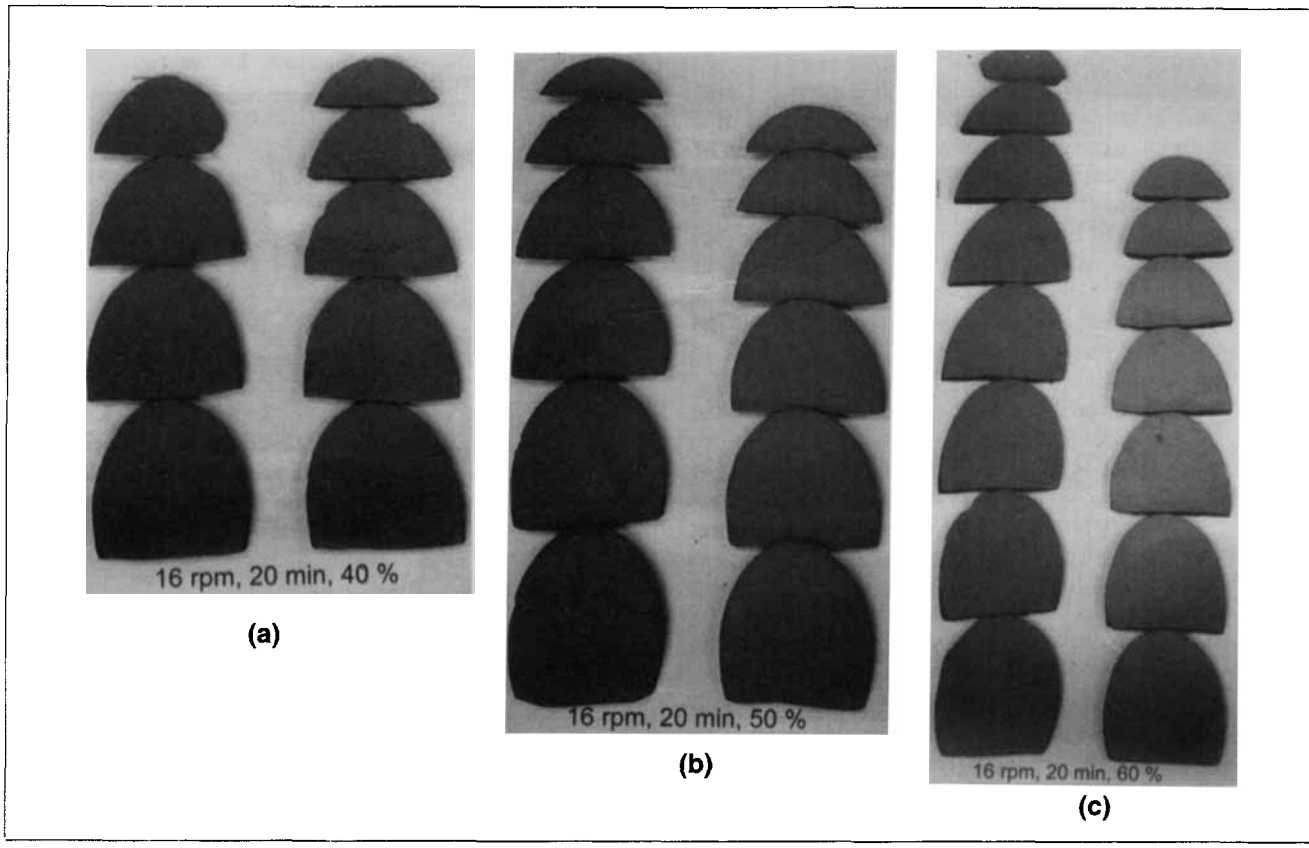

Figure 5. Effect of fill percentage on mixing for: (a) 40% fill; (b) 50% fill; (c) 60% fill.

The trends illustrated in Figures 5 and 6 are demonstrated quantitatively in Figure 7 by plotting the standard deviation of mixtures as a function of number of revolutions for fill percentages of 40%, 50% and 60% for vessels rotated at 16 rpm. The graphs show the standard deviation of samples for each experiment vs. the total number of revolutions for that experiment. The data show that as the fill is decreased, the mixing time decreases markedly. The 40% case mixes in a fraction of the time of either the 50% or 60% case. One reason for this drastic difference is that the larger fills have more particles and, thus, more particles must travel between shells to obtain complete homogeneity. Also, noting that the depth of the cascade layer of a granular material is nearly independent of bed depth for gravity-driven flows, a larger fill implies that a smaller percentage of the contents is in motion at any given time, and thus there is less mixing per unit time. To put these observations in proper context, it is noted that the filling level recommended by manufacturers is 60% (100% working capacity), and that in practical situations the pressure to decrease batch cycle time often results in processing times shorter than those corresponding to the conditions illustrated in Figure 7.

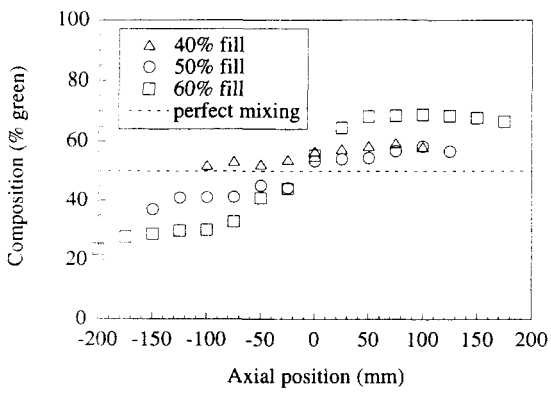

Figure 6. Axial composition profiles.

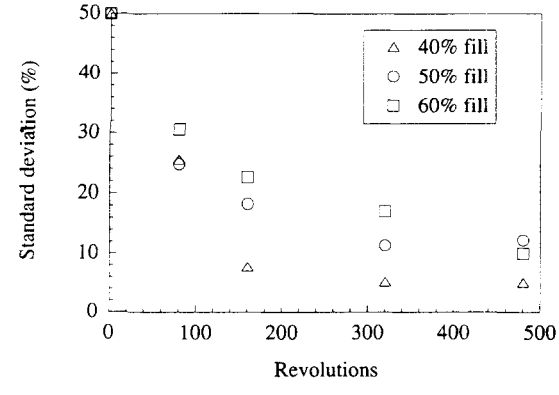

Figure 7. Effect of fill percentage on mixing.

The standard deviation is shown as a function of number of revolutions at 16 rpm.

The results just presented have implications for the operation of V-blenders in industrial operations. In many production processes, major components are loaded first and preblended, and additives or minor components are added at a layer point to finish preparation of a formulation (addition of small amounts of lubricants and glidants at the final step of a pharmaceutical production process is perhaps the most common example). Unfortunately, all too often, minor components are added to only one of the shells through a gate at the top of the shell, rather than evenly loaded in both shells (which is easily achieved by loading the vessel through the bottom valve while it is in the upside-down position). Such an uneven loading practice is likely to lead to increased heterogeneity and irreproducible results, and should be avoided whenever possible.

The experimental results just discussed demonstrate that particle flow across the plane of symmetry of the mixing vessel is the limiting step in obtaining a homogeneous mixture. Each time a V-blender rotates, the mixture is split and recombined. In the first half revolution, the mixture is split as it flows into the arms of the blender. Visualization studies in Plexiglas V-blenders have shown that particle flow across the plane of symmetry is negligible during this motion. In the second half revolution, the material in the two arms recombines in the lower part of the blender. It is in this second half revolution when all flow across the plane of symmetry occurs.

Given the experimental results presented earlier, a simple model can be constructed based on three assumptions: (1) that a constant amount of material, q, crosses the plane of symmetry in each revolution; (2) that the system is well mixed in each arm of the vessel (as suggested by Figures 5 and 6); (3) that the volume of material in each arm remains constant throughout the mixing process. Thus, a material balance on the left arm of the vessel requires that

$$M_l \frac{\partial W_l}{\partial N} = qW_r - qW_l, \tag{1}$$

where M_l is the mass of the particles in the left arm; W_l is the concentration (w/w) of the constituent of interest in the left arm; W_r is the concentration of the constituent of interest in the right arm; N is the number of revolutions; and q is the amount of material that crosses the plane of symmetry per revolution. Mass conservation requires that

$$W_r M_r + W_l M_l = m_c, \tag{2}$$

where m_c is defined as the total mass of the constituent of interest. Knowing that $M_r = M_l = M/2$, and defining $W_0 = m_c/M$, leads to

$$\frac{M}{4} \frac{\partial W_l}{\partial N} = q(W_0 - W_l). \tag{3}$$

Integrating Eq. 3 using the initial condition $W_l = 0$ at $N = 0$ gives

$$W_l = W_0(1 - e^{(-4q/M)N}), \tag{4}$$

that is, the concentration of W_l asymptotically approaches W_0 in the left arm of the vessel. Similarly, for the right arm one obtains

$$W_r = W_0(1 + e^{(-4q/M)N}), \tag{5}$$

Traditionally, mixedness of a granular system is reported in terms of mixture variance:

$$\sigma^2 = \sigma_M^2 + \sigma_R^2, \tag{6}$$

where σ_M^2 is the variance due to incomplete mixedness in the system; and σ_R^2 is the variance of a random mixture. Since by assumption the mixture composition in each arm of the vessel is constant, σ_M^2 can be estimated as

$$\sigma_M^2 = \frac{(W_0 - W_l)^2 + (W_0 - W_r)^2}{2}, \tag{7}$$

realizing that, by symmetry,

$$|W_0 - W_l| = |W_0 - W_r|, \tag{8}$$

and combining with Eq. 4 leads to

$$\sigma^2 = \sigma_R^2 + W_0^2 e^{-kN}, \tag{9}$$

where $k = 8q/M$. This model suggests that if the experiments are performed in a regime where k is independent of the rotation rate (likely to be the case for speeds much lower than critical, i.e., $Fr \ll 1$) the speed of the vessel should not affect the mixing rate per revolution. The reader should note that this approach is conceptually different from interpreting results in terms of an axial dispersion coefficient. Axial mixing in either half of the blenders occurs mainly through convection. In addition, there is a convective component of axial motion (albeit small) across the plane of symmetry, as evidenced by the folds visible in Figure 3a, showing a slice along the plane of symmetry. The conceptual distinction between convective and dispersive mechanisms is important because they suggest different approaches for enhancing mixing. If mixing is primarily dispersive, mixing would be enhanced by increasing overall particle mobility; if mixing is controlled by convective mechanisms (as is the case here), mixing should be enhanced by modifying flow patterns. In fact, as we have shown elsewhere (Brone et al., 1997), mixing in V-blenders can be greatly enhanced by increasing the magnitude of convective axial flows.

For each set of experiments, values for k and q were obtained from a least-squares fit of the data using Eq. 9. (Data points from experiments where the asymptotic variance had been reached during the experiment were not used to determine k. Since the 8 rpm experiments had the most data points before the asymptotic variance was reached, this value of k

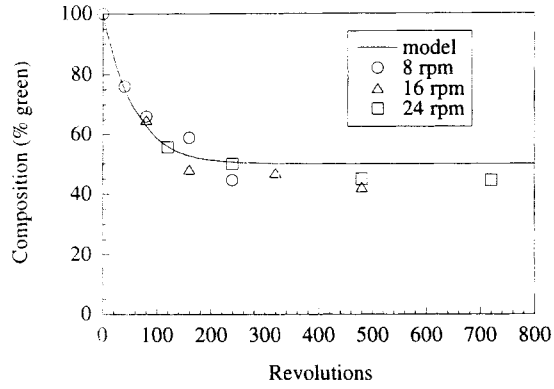

Figure 8. Model vs. experiments for: (a) variance data; (b) composition data for the originally green shell.

was used to construct the curves in Figure 8.). In Figure 8a, the experimentally determined average composition of the left arm of the V-blender (symbols) is plotted vs. number of revolutions and compared to model predictions obtained using the value of q given previously in Eq. 4. In Figure 8b, the experimentally determined variance symbols) is plotted as a function of the number of revolutions and is compared to model predictions (solid curve) obtained using the value of k from Eq. 9. Satisfactory agreement is obtained in both cases, further demonstrating that mixing in a V-blender is limited by the rate of mass transfer between halves of the mixing vessel.

While q appears to be independent of vessel speed for the conditions investigated in this article, it does depend strongly on filling level. As shown in Figure 9a, the mass flow rate through the plane of symmetry is nearly halved as fill percent increases from 40% to 60%. A 40% loading contains 560 g of particles with 1.4 g of particles crossing the vertical plane of symmetry in each revolution. The 60% fill case contains 840 g of particles, yet only 0.8 g of particles from each side is transferred between shells per revolution. Thus, not only is there a higher percentage of particles crossing the center boundary for the 40% fill, there is a higher absolute number of particles crossing the boundary per revolution as well. As a result, the decrease in mixing rate for higher loadings is even more significant when quantified in terms of $k = 8q/M$; a 40% loading will mix nearly twice as fast as a 50% loading and nearly three times as fast as a 60% loading (Figure 9b).

These observations also have implications for industrial operation of V-blenders. While it is unlikely that faster mixing would justify decreasing loading in practical cases (except perhaps in certain phamaceutical products that have a tendency to "overlubricate" if mixed for too long), the impact of filling level on mixing rates should be taken into account when batches of different sizes are manufactured in the same equipment, as is common practice in many batch industries. Moreover, during process scale-up, it is often the case that mixing processes are scaled up using completely different filling levels for the small-scale and large-scale batches. Typically, the small-scale process used for product development tends to use small filling levels in order to minimize batch size and development cost, while the large-scale process tends to use filling levels that are as large as possible in order to reach production goals while minimizing number of batches. The result of such an approach can be decreased quality of the scaled-up product. Hence, a strong recommendation is to either keep the filling level constant during scale-up, or carefully consider the effect of filling level on mixing time. The results presented here offer some guidance concerning free-flowing materials. However, it is realized that for other variables, such as particle size, shape, density, or cohesivity, the angle between the arms of the blender, the overall size of the

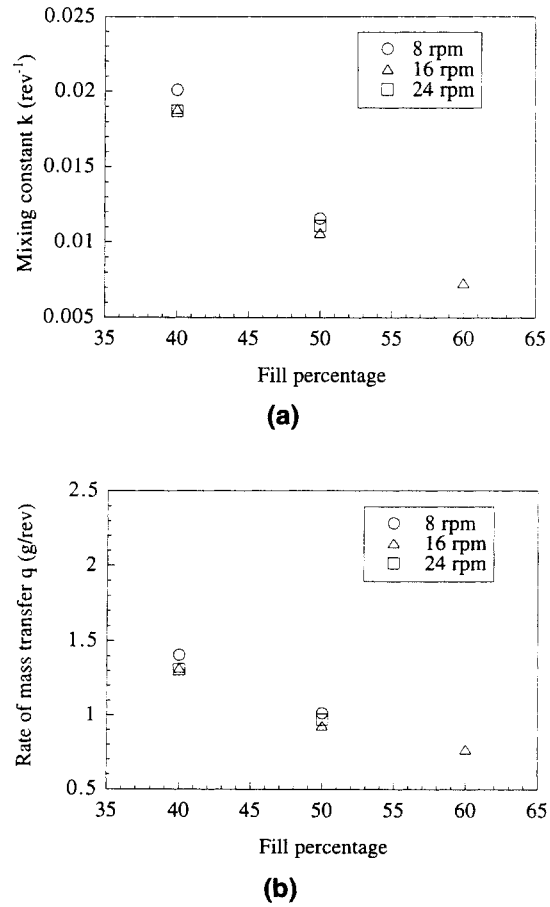

Figure 9. Effect of fill percentage on: (a) mass-transfer rate q; (b) mixing constant k.

blender, and the presence of an intensifier bar, may all affect the rate of mixing. The effect of such variables will be examined in future work.

Summary and Conclusions

An experimental approach, based on solidification, slicing, and image analysis, was used in this article to perform an accurate and extensive characterization of mixing of nonsegregating particles in V-blenders of standard configuration. The effects of vessel speed and fill percentage on the mixing rate were examined. Experimental results were also used to develop a simple model that accurately described mixing of same-size particles. Both experiments and model predictions demonstrated that the mixing process in a V-blender is directly linked to and is limited by the rate of mass transfer across the vertical plane of symmetry between the two shells of the mixing vessel.

Both vessel speed and filling level were examined to determine their effects on mixing rate. For rotation rates between 8 and 24 rpm, the mixing mechanisms were essentially unchanged. In all cases, mixing time was inversely proportional to vessel speed, and similar degrees of homogeneity were obtained for mixtures rotated for the same number of revolutions. Vessel filling level, on the other hand, had a substantial effect on mixing rate. As the vessel fill rate was increased, motion within the vessel was inhibited, particle mobility across the symmetry plane was decreased, and mixing times were increased.

These observations have three implications for the use of V-blenders in industry. First, the V-blender should be loaded with equal amounts of each component loaded on each side of the plane of symmetry. Second, sampling of the mixture should be done equally on both sides of the plane of symmetry. Data taken from only one side of the vessel may indicate that the mixture is homogeneous, while a difference in compositions between halves may exist. Third, scale-up procedures should either keep the filling level constant, or should take into account the effect of filling level on mixing rate.

Literature Cited

Adams, J., and A. Baker, "An Assessment of Dry Blending Equipment," *Trans. Inst. Chem. Eng.*, **34**, 91 (1956).

Berman, J., and J. A. Planchard, "Blend Uniformity and Unit Dose Sampling," *Drug Dev. Ind. Pharm.*, **21**(11), 1257 (1995).

Brone, D., C. Wightman, K. Connor, A. Alexander IV, F. J. Muzzio, and P. Robinson, "Using Flow Perturbations to Enhance Mixing of Dry Powders in V-Blenders," *Powder Technol.*, **91**, 165 (1997).

Cahn, D. S., D. W. Fuerstenau, T. W. Healy, R. Hogg, and H. E. Rose, "Diffusional Mechanism of Solid-Solid Mixing," *Nature*, **209**, 494 (1966).

Cahn, D. S., T. W. Healy, and D. W. Fuerstenau, "Blending Geometry in the Mixing of Solids," *Ind. Eng. Chem. Prod. Res. Dev.*, **4**, 318 (1965).

Carley-Macauly, K. W., and M. B. Donald, "The Mixing of Solids in Tumbling Mixers—I," *Chem. Eng. Sci.*, **17**, 493 (1962).

Carley-Macauly, K. W., and M. B. Donald, "The Mixing of Solids in Tumbling Mixers—II," *Chem. Eng. Sci.*, **19**, 191 (1964).

Carstensen, J. T., and M. R. Patel, "Blending of Irregularly Shaped Particles," *Powder Technol.*, **17**, 273 (1977).

Chang, R.-H., S. Badawy, M. A. Hussain, and J. D. Buehler, "A Comparison of Free-Flowing, Segregating and Non-Free-Flowing, Cohesive Mixing Systems in Assessing the Performance of a Modified V-Shaped Solids Mixer," *Drug Dev. Ind. Pharm.*, **21**(3), 361 (1995).

Chang, R.-K., S.-I. Chang, and J. R. Robinson, "A Study of the Performance of a Modified V-Shaped Solids Mixer Using Segregating Materials," *Int. J. Pharm.*, **80**, 171 (1992).

Chowhan, Z. T., and E. E. Linn, "Mixing of Pharmaceutical Solids. I. Effect of Particle Size on Mixing in Cylindrical Shear and V-Shaped Tumbling Mixers," *Powder Technol.*, **24**, 237 (1979).

Donald, M. B., and B. Roseman, "Mixing and Demixing of Solid Particles Part I: Mechanisms in a Horizontal Drum Mixer," *Brit. Chem. Eng.*, **7**(10), 749 (1962).

Fan, L. T., S. J. Chen, and C. A. Watson, *Annual Review of Industrial and Engineering Chemistry, 1970, I&EC Annual Review*, V. M. Weekman, ed., Amer. Chem. Soc., Washington, DC, p. 22 (1972).

Fan, L. T., Y.-M. Chen, and F. S. Lai, "Recent Developments in Solids Mixing," *Powder Technol.*, **61**, 255 (1990).

Gayle, J. B., O. L. Lacey, and J. H. Gary, "Chi Square as a Criterion," *Ind. Eng. Chem.*, **50**(9), 1279 (1958).

Gopinath, S., and R. Vedaraman, "A Vibrating Mixer for Mixing Particulate Solids," *Res. & Ind.*, **27**, 321 (1982).

Gray, J. B., "Performance of Dry Solids Mixing Equipment," *Chem. Eng. Prog.*, **53**(1), 25 (1957).

Harnby, N., "A Comparison of the Performance of Industrial Solids Mixers Using Segregating Materials," *Powder Technol.*, **1**, 94 (1967).

Harwood, C. F., K. Walanski, E. Luebcke, and C. Swanstrom, "The Performance of Continuous Mixers for Dry Powders," *Powder Technol.*, **11**, 289 (1975).

Henein, H., J. K. Brimacombe, and A. P. Watkinson, "Experimental Study of Traverse Bed Motion in Rotary Kilns," *Metall. Trans.*, **14B**, 191 (1983).

Hogg, R., D. S. Cahn, T. W. Healy, and D. W. Fuerstenau, "Diffusional Mixing in an Ideal System," *Chem. Eng. Sci.*, **21**, 1025 (1966).

Hogg, R., and D. W. Fuerstenau, "Transverse Mixing in Rotary Cylinders," *Powder Technol.*, **6**, 139 (1972).

Kaufman, A., "Mixing of Solids," *Ind. Eng. Chem. Fundam.*, **1**, 104 (1962).

Lai, F., and J. A. Hersey, *Ind. Chem. Eng. Symp. Ser. No. 65*, The Institution of Chemical Engineers, p. S1/C (1981).

Masiuk, S., "Power Consumption, Mixing Time and Attrition Action for Solid Mixing in a Ribbon Mixer," *Powder Technol.*, **51**, 217 (1987).

Muzzio, F. J., P. Robinson, C. Wightman, and D. Brone, "Sampling Practices in Powder Blending," *Int. J. Pharm.* (1997).

Orr, N. A., and E. Shotton, "The Mixing of Cohesive Powders," *Chem. Eng., London*, **269**, 12 (1973).

Poole, K. R., R. F. Taylor, and G. P. Wall, "Mixing Powders to Fine-Scale Homogeneity: Studies of Batch Mixing," *Trans. Inst. Chem. Eng.*, **42**, T305 (1964).

Poux, M., P. Fayolle, J. Bertrand, D. Bridoux, and J. Bousquet, "Powder Mixing: Some Practical Rules Applied to Agitated Systems," *Powder Technol.*, **68**, 213 (1991).

Samyn, J. C., and K. S. Murthy, "Experiments in Powder Blending and Unblending," *J. Pharm. Sci.*, **3**, 370 (1974).

Schofield, C., "The Definition and Assessment of Mixture Quality in Mixtures of Particulate Solids," *Powder Technol.*, **15**, 169 (1976).

Wiedenbaum, S. S., *Advances in Chemical Engineering*, Vol. II, T. B. Drew and J. W. Hoopes, eds., Academic Press, New York, p. 209 (1958).

Wightman, C., P. R. Mort, F. J. Muzzio, R. E. Riman, and E. K. Gleason, "The Structure of Mixtures of Particles Generated by Time-Dependent Flows," *Powder Technol.*, **84**, 231 (1995).

Wightman, C., F. J. Muzzio, and J. Wilder, "A Quantitative Image Analysis Method for Characterizing Mixtures of Granular Materials," *Powder Technol.*, **89**, 165 (1996).

Williams, J. C., and M. I. Khan, "The Mixing and Segregation of Particulate Solids of Different Particle Size," *Chem. Eng., London*, **269**, 19 (1973).

Manuscript received May 23, 1997, and revision received Nov. 3, 1997.