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V-blender segregation patterns for free-flowing materials: effects of blender capacity and fill level

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Abstract

Stable segregation patterns are shown to form in V-blenders over a wide range of vessel capacities, fill levels, and rotation rates. Slight changes in either rotation rate or fill level induce changes in pattern formation. Trajectory segregation in two regions of the flow, accumulating over many flow periods, drives segregation pattern formation. Scaling criteria derived to relate particle velocities to vessel size and rotation rate in rotating cylinders successfully predict the rotation rate for the transition between patterns across V-blenders of 0.8–26.5 quart total capacity. This agreement suggests that pattern formation is governed by the magnitude of particle velocities. Regardless of vessel size, when particle velocities at specific regions of the blender are below a certain value, one particular pattern appears, and when they increase beyond that speed (i.e. by changing the rotation rate or the vessel size), a different pattern emerges. A scaling relation between segregation pattern formation and blender fill level was not identified because the complex flow patterns in the V-blender (the length of the flowing layer and the mixture center of mass relative to the blender are constantly oscillating) preclude the determination of a relationship between blender fill level and particle velocities.

Keywords: Tumbling blenders; Segregation; Scale-up

1. Introduction

The V-blender is one of the tumbling blenders most commonly used in the pharmaceutical industry for mixing powders and granular materials. Several previous studies have looked at both mixing (Brone et al., 1998; Brone et al., 1997; Cahn et al., 1965; Carstensen and Patel, 1977; Chang et al., 1995; Chang et al., 1991; Chowhan and Linn, 1979; Kaufman, 1962; Wiedenbaum, 1963) and segregation tendencies (Adams and Baker, 1956; Alexander et al., 2001; Harnby, 1967; Harwood et al., 1975; Lai and Hersey, 1981; Samyn and Murthy, 1974) in this device. General reviews of tumbling blenders can be found in (Fan et al., 1972; Fan et al., 1990; Poux et al., 1991). Previously, three distinct segregation patterns have been shown to form in a 1.9 quart capacity V-blender when filled to 50% of total capacity with a 50/50 mix by volume of 775 and 200 μ glass beads (Alexander et al., 2003). At these conditions, the segregation patterns that developed were shown to depend solely on the rotation rate of the blender (Fig. 1). Each pattern would form for specific ranges of rotation rate; small increases in rotation rate (<0.5 rpm) induced a

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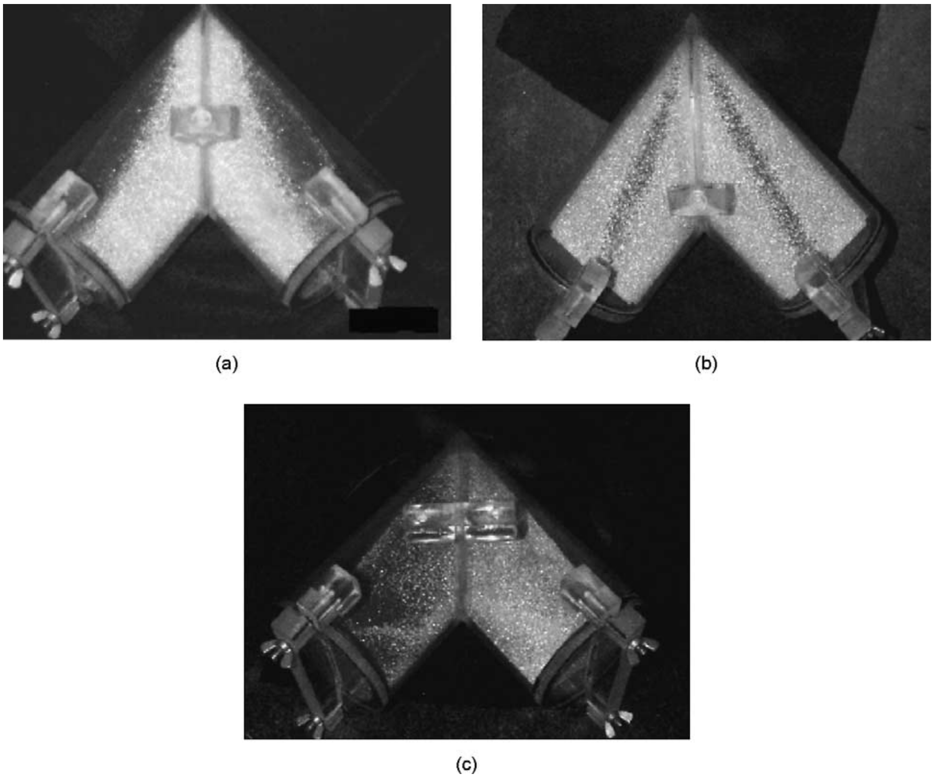

Fig. 1. The three segregation patterns found in the 1 quart V-blender when run at 50% of capacity. (a) At low rotation rates (<7.5 rpm), the 'small-out' pattern forms; (b) intermediate speeds (7.9–19 rpm) produce 'stripes'; and (c) high rotation rates (>19.3 rpm) induce 'left–right' segregation.

change from one pattern to another (these transitions are discussed in detail in Alexander et al., 2003). This communication seeks to further this work by looking at how changing the fill level (fraction of vessel capacity occupied by the mixture) or size of the vessel affects segregation pattern formation. Transitions from one pattern to another are used as a marker of kinematic and dynamic similarity for the purposes of studying scaling rules for tumbling blenders.

2. Background

Pharmaceutical formulations are typically developed in lab scale tumbling blenders; as the development process continues towards commercialization, larger equipment is used. However, scaling granular processes remains an art dependent on heuristics and empiricism rather than rigorous rules based on a fundamental understanding of the underlying dynamics. Currently there is no generally accepted method for determining the change in operational parameters governing an increase in equipment size. The most commonly recommended method for scaling granular systems involves the use of the Froude number ($Fr \equiv \Omega^2 R/g$; where Ω is the rotation rate, R is the radius, and g is the acceleration due to gravity). Fr is widely used in fluid mechanics to describe the balance between inertial forces and gravitational forces. Miyanami (1980), Wiedenbaum (1958), and Lloyd et al. (1970) asserted that tumbling blenders can be scaled simply by matching Fr. Wang and Fan (1974) suggested using Fr to assure dynamic similarity in tumbling blenders and scale-up of the mixing process was then dependent on a Fickian-based diffusion equation but no experimental evidence was shown to support this assertion. Roseman and Donald (Donald and Roseman, 1962; Roseman and Donald, 1962) stated that radial segregation in a rotating cylinder is scaled by Fr and the particle size ratio. Bytnar et al. (1995) tested this hypothesis in a 5 and10 cm drum and found significant differences at similar Fr. However, these experiments were also run at substantially different fill levels in the two vessels. Furthermore, Pouliquen (1999) showed that the velocities of particles traveling down inclined surfaces collapsed into a straight line when expressed in terms of Fr and the function h/h_{stop}, where h_{stop} is the critical layer thickness at which flow ceases.

Other analyses of scaling criteria include a study by Williams and Khan (1973) which showed that the standard deviation (σ) of a segregating mixture of fertilizer pellets followed $\sigma \propto V^{-1/2}$, where V is the blender capacity. However, the authors cautioned that this result was only valid in the range of capacities tested (1.9–15.0 quarts) and that the effectiveness of this scale-up method was expected to diminish with increasing capacity. In a previous study, we showed that particle velocities in rotating cylinders (i.d. 6.3–24.5 cm) were accurately scaled by:

$$v \propto R\Omega^{2/3}\left(\frac{g}{d}\right)^{1/6}; \quad \Omega < 30\,\text{rpm}, \tag{1}$$

where v is the particle velocity, R is the cylinder radius, d is the particle diameter, and Ω is the rotation rate (Alexander et al., 2002). Herein, we show that this criterion can be used to scale transitions for V-blender segregation patterns at fixed fill level with changes in rotation rate and total vessel capacity from 0.8 to 26.5 quarts.

3. Experimental

Five different sized vessels were used; each blender is named according to the volume of material that is necessary to fill the blender to approximately 60% of total capacity (100% of manufacturer's recommended capacity). The two smallest blenders (1 pint and 1 quart) were designed to be fastened within a plexiglass cylinder that was rotated on a pair of roller bars. The three large blenders are commercially available vessels from Patterson–Kelly as part of the Blendmaster series (Patterson–Kelley Co., East Stroudsburg, PA 18301). Vessel dimensions are shown in Table 1 along with a schematic in Fig. 2.

Table 1
Vessel dimensions

Nominal capacity	Vessel volume (quarts)	L (cm)	R (cm)	D (cm)	θ (°)
1 pint	0.8	10.5	7.9	6.7	80
1 quart	1.9	13.9	10.6	9.2	80
4 quart	6.5	21.2	14.6	13.8	75
8 quart	12.9	24.7	18.8	17.6	75
16 quart	26.5	33.0	24.2	21.6	75

See Fig. 2 for sketch showing L, R, D, and θ

All the vessels are constructed from clear Plexiglas, enabling visual identification of segregation patterns. The V-blender is also known as the twin-shell blender; some of the ensuing discussion will refer to a single 'shell,' which is simply the left or right half of the blender.

For the experiments discussed herein, a binary mixture of glass beads was used. The mixture consisted of sieved fractions of 150–250 μ particles (nominally 200 μ) and 710–840 μ particles (nominally 775 μ) with the smaller particles dyed red and the larger particles dyed yellow. These materials were chosen to accentuate the formation of segregation patterns in the blender and represent a worst-case scenario. The mixture distributions seen in Fig. 1 are unlikely to take place for typical pharmaceutical mixtures. If segregation occurs, similar patterns could evolve but the degree of separation is unlikely to be as extreme (i.e. the segregated regions would not be near 100% of each component).

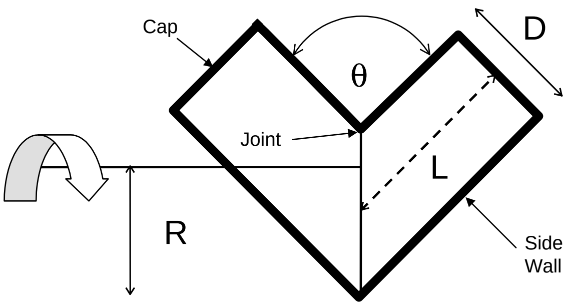

Fig. 2. A sketch showing the various dimensions for a V-blender, the measured values for the five blenders used in this study are shown in Table 1. R is measured as half the total blender height perpendicular to the axis of rotation and L is measured along the dashed line.

Experiments were performed in the following manner: a specified amount of each material was weighed, corresponding to an equivalent volume of each particle size. The larger beads were added to the blender first and leveled. Subsequently, the smaller beads were carefully poured on top and leveled. This procedure gave a symmetric initial condition with respect to the blender geometry. This symmetric top/bottom loading scheme is similar to industrial practice which often directs that all material should be loaded when the V-blender is inverted to ensure equal loading into both shells. The blender was run at constant rotation rate; a segregation pattern was assumed to be stable when it did not discernibly change for 100 revolutions. This timeframe is relevant to typical industrial blending times of 100–200 revolutions and lubrication times of 30–100 revolutions.

4. Results and discussion

4.1. Blender size effects

Previously, changing rotation rate at a fixed fill level (50%) was shown to induce a transition from the 'small-out' to the 'stripes' pattern in the 1 quart blender near 7.5 rpm (Alexander et al., 2003). This transition occurred with a change in rotation rate of less than 0.5 rpm. Similar patterns have been reported to form in double cone blenders using a wide range of particle sizes (Alexander et al., 2001). Experiments were undertaken to determine the transition speeds (rotation rates) for the change from the 'small-out' pattern to 'stripes' at 50% fill for all the blenders listed in Table 1. Table 2 shows the results of these experiments, indicating the highest rotation rate for which 'small-out' were noted and the lowest for which 'stripes' were seen—the average of these two is taken to be the transition rotation rate.

Table 2
Pattern transition rotation rates

Blender size	Last 'small-out'	First 'stripes'	Transition (rpm)
1 pint	9	10	9.5
1 quart	7.5	7.9	7.7
4 quart	3	4	3.5
8 quart	2	3	2.5
16 quart	1.4	2	1.7

Table 3
Parameter values at transition rotation rate

Blender size	Fr, $\Omega^2 R/g$ ($\times 10^5$)	Tangential velocity, $2\pi\Omega R$ (cm/s)	$R\Omega^{2/3}(g/d)^{1/6}$ (cm/s)
1 pint	20.2	7.9	12.1
1 quart	17.8	8.5	14.1
4 quart	5.1	5.4	11.5
8 quart	3.3	4.9	11.8
16 quart	2.0	4.3	11.7

The data in Table 2 demonstrate an inverse relationship between rotation rate and blender size. The data from Table 1 indicate that, as the blender size is increased, this transition from 'small-out' to 'stripes' will disappear and the 'small-out' pattern will no longer form in the blender. Another transition from 'stripes' to 'left–right' also takes place (see Fig. 1 and Alexander et al., 2002) but is harder to determine visually. Furthermore, the geometry of the larger vessels, which have an attachment for the rotating arm protruding into the mixing chamber also intrudes on the "normal" flow patterns in one shell of the blender. This protrusion enhances the formation of 'left–right' patterns and makes determination of the crossover rotation rate exceedingly difficult. Even so, it is likely that similar results to those in Table 1 would be applicable to the 'stripes' to 'left–right' transition.

As discussed in the introduction, the most commonly accepted methods for scaling tumbling blenders have used one of two parameters, either the Froude number (Fr) or the tangential speed of the blender. In a previous communication, we showed that neither of these parameters accurately scaled surface velocities of particles in rotating cylinders with changes in rotation rate and/or cylinder diameter. The parameter $R\Omega^{2/3}(g/d)^{1/6}$, was shown to effectively scale particle velocities when the rotation rate is below 30 rpm ($R\Omega^{1/2}(g/d)^{1/4}$ is employed above 30 rpm (see Alexander et al., 2002 for details). We note that all three of these criteria indicate an inverse relationship between rotation rate and blender size. In Table 3, we show the parameter values at the transition rotation rate for $R\Omega^{2/3}(g/d)^{1/6}$, Fr, and the tangential velocity.

In these calculations, the average particle size, 487.5 μ, is used for d. The $R\Omega^{2/3}(g/d)^{1/6}$ parameter gives much better agreement than either Fr or tangential velocity; the relative standard deviation for $R\Omega^{2/3}(g/d)^{1/6}$ is 8.6%, compared to 89% for Fr and 30% for tangential velocity. Notably, the value of $R\Omega^{2/3}(g/d)^{1/6}$ for the 1 pint and 16 quart vessels are nearly identical while for Fr there is an order of magnitude difference and the difference is nearly twofold for tangential velocity. The agreement with $R\Omega^{2/3}(g/d)^{1/6}$ values indicates that pattern formation may be driven by the magnitude of particle velocities because particle velocities have been shown to scale with $R\Omega^{2/3}(g/d)^{1/6}$. In other words, regardless of vessel size, the magnitude of particle velocities along specific trajectories of the blender determine which segregation pattern will arise in the blender. The next section looks at segregation mechanisms and how different segregation patterns form with changes in particle velocities.

4.2. Mechanisms

Two regions of the flow have been identified as important for determining which segregation pattern will form (see Alexander et al., 2003 for details). Changes in segregation mechanisms as a function of rotation rate of the blender (at fixed fill level) are summarized here. One region is near the joint of the blender, where the mixture splits in two during the V to Λ phase of the rotation. At low rotation rates, trajectory segregation induced by surface flow separates large and small particles. At this location, the mixture of large and small particles enters a bend in the flow, where the small particles change direction while the large particles (more inertial and with less surface friction/unit mass) will travel further in the original flow direction before turning (Fig. 3a). Small particles collect on the concave side of the bend (the middle of the shell), while large particles concentrate on the convex side (the middle of the blender). At higher rotation rates, however, particle velocities increase and the mixture 'crashes' into the joint. Small particles percolate through the mix while large particles remain on the surface (Fig. 3b, this process is similar to pouring a binary mixture into a heap). This effectively reverses the trends seen at low rotation rates; for high rotation rates, small particles gather near the center of the blender

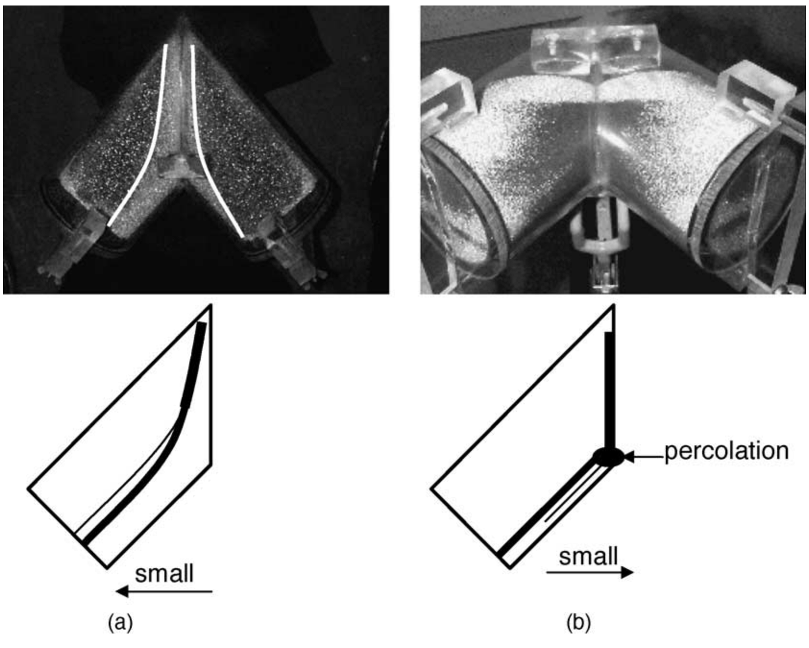

Fig. 3. Segregation mechanisms near the joint of the blender. When a mixture of large and small particles flows through a bend at (a) low rotation rates, large particles travel through bends in the pathlines; small particles follow the bend and gather in the middle of the shell. (b) At higher rotation rates, the mixture 'crashes' into the joint, small particles percolate through the mix; large particles travel further towards the caps, leaving small particles to gather near the joint of the blender.

while large particles move into the center of each shell.

The other important region is near the side walls of the blender. In this region, once again, the process is controlled by trajectory segregation at both high and low rotation rates, although in different phases of the blender rotation. At low rotation rates, as the mixture flows towards the caps, friction with the side walls as well as hills and slopes formed due to the blender geometry induce a curved flow that sends large particles towards the center of the shell and traps small particles near the side wall (Fig. 4a). At higher rotation rates, these pathlines straighten out, lessening the extent of trajectory segregation. In addition, during the other half of a single rotation, flow towards the wall exhibits a turn that also induces trajectory segregation, but, in this case, it sends large particles towards the walls and small ones to the center of the blender (Fig. 4b, i.e. the opposite of what occurs in Fig. 4a). We surmise that both of these flow patterns exist at all rotation rates but that one dominates, depending on particle velocities.

Pattern formation is then determined by relative motions of large and small particles in these two areas of the blender. In order for distinct patterns to form, it is very important that the two components in the mixture flow independently—adding cohesion to the mixture (which can be done with water or static charge for mixtures of glass beads) eliminates or greatly reduces the intensity of these segregation patterns. For other mixtures with cohesive components, these segregation patterns are unlikely to form nearly as distinctly as seen here, if at all.

At both the side walls and the joint, there are two segregation possibilities, each having opposite effects. Depending on process conditions, specific pairings of these mechanisms produce the various segregation patterns shown in Fig. 1. Each of the mechanisms described in this section can be defined as occurring for ‘slow’ or ‘fast’ particle velocities. At a given rotation rate, the absolute values of particle velocities at these two locations may not vary much but each mechanism likely has a different velocity at which it switches from ‘slow’ to ‘fast’. The different pairings of these

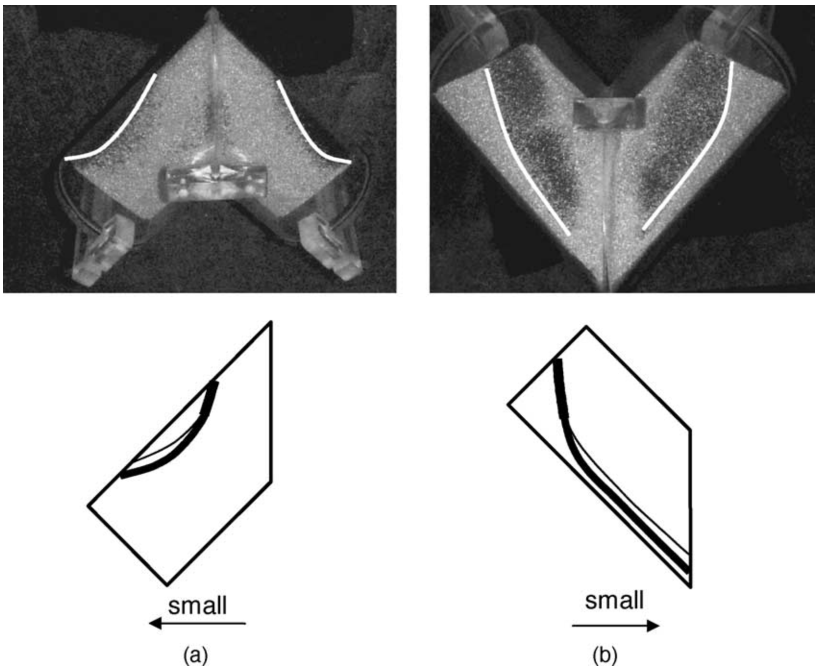

Fig. 4. Changes in segregation behavior near the side wall with variations in rotation rate at 50% fill. (a) Trajectory segregation at low rotation rates keeps small particles (red) pinned near the side. At higher rotation rates, mixture flow patterns during the Λ to V phase of the rotation (b) induce trajectory segregation that sends small particles towards the center of the shell.

Table 4
Segregation patterns relationship to particle velocities

Velocities at wall	Velocities at joint	Pattern outcome
Slow	Slow	Small-out
Slow	Fast	New pattern?
Fast	Slow	Stripes
Fast	Fast	Left–right

mechanisms would then drive the formation of segregation patterns, and are summarized in Table 4.

In Table 4, we see that this analysis indicates that a fourth pattern could also form within the V-blender. Further experiments in the 1 quart V-blender were run varying both the fill level and the rotation rate of the blender and are discussed in the next section.

4.3. Effects of fill level

At a single rotation rate at fixed fill level, we found small increases in fill level (as little as 1%) could induce variations in segregation patterns, analogous to changing rotation rate. Moreover, a fourth pattern became evident. This pattern, for which large particles form a stripe in the middle of each shell, is named 'inverse stripes' as it is the opposite of the pattern shown in Fig. 1b. Fig. 5 shows the four patterns that emerge at various fill levels (30–70%, by volume) at 8 rpm. The 'big out' pattern shown in Fig. 5d was an unstable intermediate that leads to 'left–right' when run at 50% fill in a 1 quart V-blender (Alexander et al., 2003). By changing the fill level in the blender, we determined that 'big-out' is in fact stable for hundreds of revolutions when the fill level is below ∼40%.

The combined effects of rotation rate and filling were investigated in the 1 quart blender covering from 30 to 70% filling and 4–30 rpm, however, a slightly different mixture (720 μ, sieved 600–840 and 215 μ, sieved 180–250, particles) was used that reduced static charging at higher rotation rates. The results were similar at 50% fill and a V-blender segregation pattern diagram was constructed from all the data (Fig. 6). Both the 'small-out' and 'inverse stripes' patterns are suppressed at higher rotation rates (>12 rpm) and

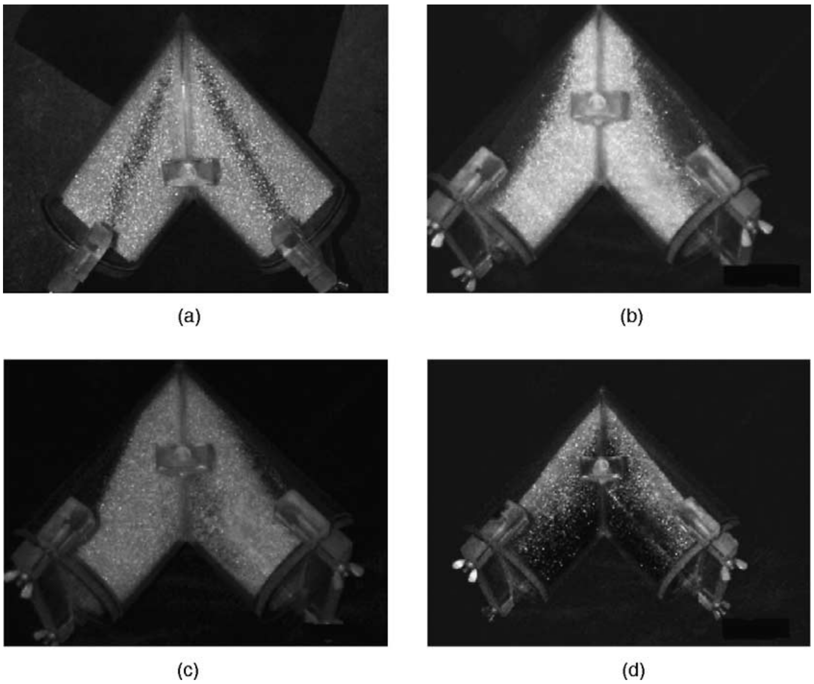

Fig. 5. Segregation patterns that form in the 1 quart V-blender at 8 rpm. At high fill levels (54–80%): (a) the 'stripes' pattern forms; (b) decreasing the fill percent brings about transitions to 'small-out' (43–49%); (c) 'inverse stripes' (35–42%); and (d) 'big-out/left–right' (30–34%).

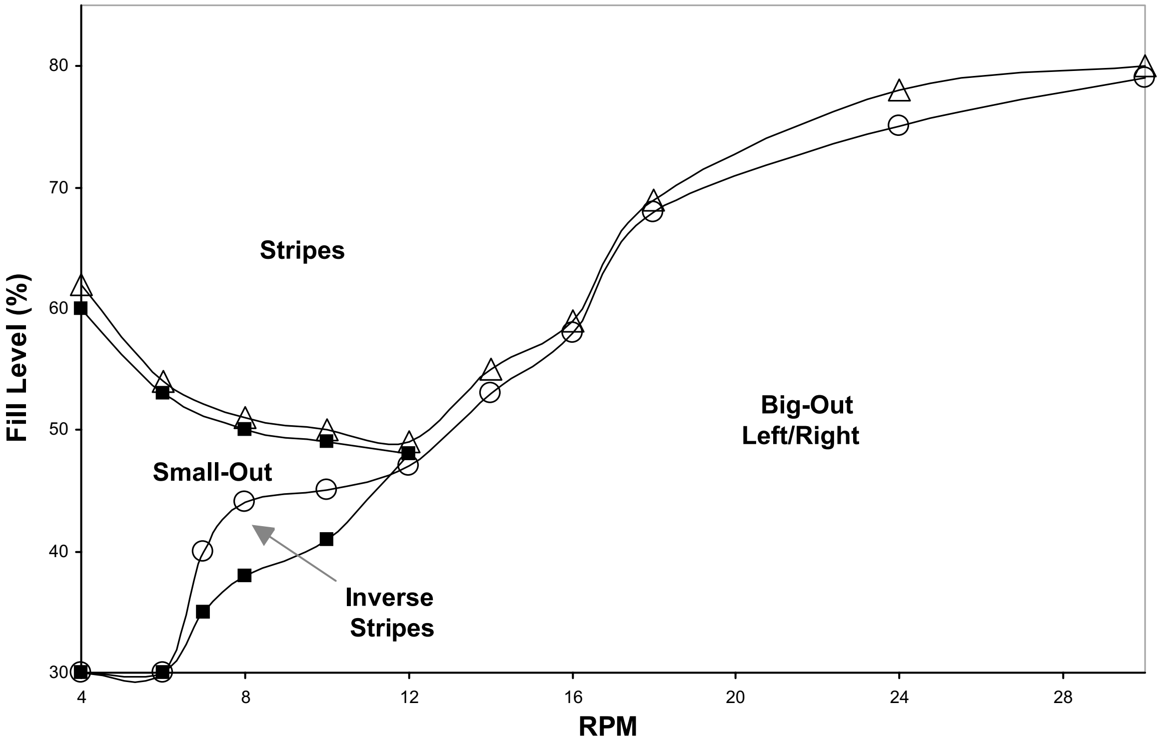

Fig. 6. The V-blender segregation pattern diagram, showing the influence of both filling and rotation rate on pattern development in the 1 quart blender (note: a mixture with slightly different sizes than that shown in Figs. 1 and 3–5 was used to generate this data, see text for explanation).

increased fill levels. Only 'stripes' is seen across all rotation rates, but it does not appear below 50% fill. The 'big-out/left–right' patterns dominate the higher rotation rates (>14 rpm) and are the most common patterns. In concept, this pattern diagram could be constructed for any strongly segregating mixture and any V-blender. It is likely that larger vessels will exhibit the same general tendencies but that the specific ranges of fill levels and rotation rates would vary. There is a certain ambiguity in determining the change from one pattern to another, especially for 'left–right' to 'stripes' and anytime 'inverse stripes' is involved. The exact transitions from one pattern to another can vary with slight changes in vessel geometry (tilt, twist, etc.) such that Fig. 6 should be taken as indicative of general changes in pattern behavior with a certain degree of variability (±0.5 rpm, 1–2% fill) at most transitions.

A general feature of Fig. 6 is that the transitions between patterns are associated with a change in only one of the two mechanisms from 'slow' to 'fast' or vice versa. Hence, in order to change from 'small-out' (slow, slow) to 'left–right' (fast, fast), an intermediate pattern, either 'inverse stripes' (slow, fast) or 'stripes' (fast, slow) must first be traversed. This indicates that the two regions that drive pattern formation are not interdependent and can be considered separately. Additionally, this means that marking the transition from 'small-out' to 'stripes' or stripes' to 'left–right' marks a change in flow (segregation mechanism) at a specified region in the blender and is not an indication of a global change in mixture behavior.

5. Conclusion

Segregation patterns for free-flowing binary-distributed mixtures in V-blenders ranging in total capacity from 0.8 to 26.5 quarts have been shown to vary with changes in rotation rate at equivalent fill level (percent of capacity occupied by the mixture). In a 1.9-quart vessel, patterns were also shown to vary simply with changes in fill level at constant rotation rate. The mechanisms that drive pattern formation appear to depend on particle velocities in two specific regions of the blender. Segregation patterns change when velocities cross a specific threshold, regardless of the size of the vessel or the fill level.

A scaling relation that relates particle surface velocities in rotating cylinders to vessel size and rotation rate accurately predicts the rotation rate for the transition between 'small-out' and 'stripes' at 50% fill in vessels of differing capacity. A similar scaling relation was not obtained for the transitions between various patterns with changes in fill level at constant rotation rate. In the V-blender, the length of the flowing layer and the mixture center of mass (relative to the blender) are constantly in flux, complicating comparisons of blender dynamics with just a few percent difference in fill level. Furthermore, the changes in particle velocities at specific locations in the blender may not scale similarly with changes in fill level. Thus, because blender pattern formation is independently reliant on particle velocities at different locations in the blender, it may be impossible to accurately scale these changes, even if particle velocities were measured at all fill levels.

Finally, we also caution that the blenders used in this study are still small relative to industrial or pilot-plant sized vessels and that these patterns will only appear for strongly segregating free-flowing materials. Further applications of this work would include determining whether this scaling approach works in larger vessels and to examine whether these results are transferable to systems involving more cohesive materials.

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