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Characterization of Granular Flow of Wet Solids in a Bladed Mixer

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DOI 10.1002/aic.10868
Published online May 4, 2006 in Wiley InterScience (www.interscience.wiley.com).

In this study, we measure instantaneous, average, and fluctuating velocity fields at exposed surfaces for dry and wet grains in a vertical cylindrical mixer, agitated by four pitched blades. When the material is dry, the free surface of the granular bed deforms, rising where the blades are present, and falling between blade passes. Although average velocities are predominantly azimuthal, instantaneous velocities tracked in time reveal three-dimensional particle circulations, including significant periods of particle motion in the opposite direction to that of the blades, indicative of bed penetration. When moisture is added to the solid particles, the flow dynamics change from a regime dominated by the motion of individual grains to a regime controlled by the motion of small clumps that form as a result of the cohesive forces. This transition is characterized by a reduced particle–particle collision frequency and exhibits a sharp decrease in the granular temperature at the free surface. This transition is also characterized by an increase in bed porosity, which is attributed to increased cohesiveness arising from liquid bridges. A Fourier transform analysis conducted on the tangential component of the velocities (dominant flow) shows that a group of high frequencies exceeding the blade rotation frequency become significant with added moisture. These are characteristics of the large number of wet agglomerates flowing between successive blade passes. © 2006 American Institute of Chemical Engineers *AIChE J,* 52: 2757–2766, 2006
Keywords: granular material, granular temperature, wet cohesion, PIV, pharmaceuticals

Introduction

Bladed mixers are commonly used in a variety of areas, ranging from the bulk chemical to the food and pharmaceutical industries. In the majority of these processes, agitated mixers are used to homogenize or granulate a mixture of solid particles, to enhance chemical reactions, or to improve heat and mass transfer, as in agitated filter dryers. Despite their extensive use, the flow of granular materials in agitated devices and the mechanisms by which particle motion is generated are still not fully understood. The majority of past studies have focused on dry granular materials.[1-8] The more complicated and more frequently encountered case of agitated granular material in the presence of significant moisture has received less attention. Little is known about velocity fields and flow patterns of wet materials and their impact on particle properties and particle size changes (particle breakage and agglomeration). Thus, the aim of this paper is to elucidate some basic features of the solid flow patterns and velocity profiles of wet granular materials in mechanically agitated beds. This is important for scale-up and control of granular processes. This information may also serve to validate simulation codes, which have the potential to describe with great accuracy the physical phenomena occurring in such systems at a microscopic level.

Flows of discrete particles are difficult to characterize because they exhibit a vast range of behavior, from solid-like, quasi-static flows to rapid fluid-like ones.[9] Adding moisture to the system adds to the difficulty of predicting the associated particle flow patterns and velocity fields. The most prominent effect of adding modest amounts of moisture to dry particles is

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an increase in interparticle cohesiveness,[10] which directly influences the bulk flowability of the solid material. Increased cohesiveness can cause jamming of the flow, even under conditions where the dry material flows.[11] Depending on the moisture content, the wet particles can exist in a number of different states, from pendular (low moisture content) to funicular (intermediate moisture content) and capillary states (high moisture contents).[12] When the interstitial space between particles is partially filled with moisture, a series of liquid bridges develop, pulling adjacent particles together. Tensile strength can be maintained as long as the liquid does not extend beyond the exposed particle surface.[10]

Most of the research on granular flows of wet materials has focused on simple geometrical situations, such as a pair of spherical particles held by a liquid bridge, sand piles, inclined planes, Couette systems, or cylindrical tumblers. The majority of these efforts were devoted to develop mathematical models that can describe the behavior of the wet granules at the macroscopic level based on particle dynamics simulations.[13] Such methods describe the flow of material by simultaneous integration of the interaction forces between individual pairs of particles.[14] To the best of our knowledge, the modeling of wet particle interactions has not been extended to more complex bladed-mixer geometries. Mixing studies of wet materials in bladed mixers (such as wet granulation, high shear mixing, agitated drying) are mostly directed toward understanding and predicting the effect of process parameters, such as agitation speed, temperature, or moisture content on the final particle properties (size distribution, shape distribution, hardness, etc.).

Measurements taken in agitated blenders are limited to samples removed from specified locations for off-line analysis and to on-line measurement of a limited set of process parameters. An example of the latter is measurement of agitator torque[15] or stress fluctuations[16] to monitor agglomeration during wet granulation, which has been shown to be able to determine transitions from wet to dry or nearly dry materials. Surface velocity measurements have also been performed during a moisture addition process in high-shear granulators and were found to reflect changes in shear transmission as a result of wetting.[17] A more detailed characterization of flow patterns is also possible by bed freezing (by solvent infiltration and setting) and dissection.[2-4,18-21] Recent studies of particle mixing are based on newly advanced noninvasive techniques, such as particle image velocimetry (PIV),[22,23] which is a two-dimensional (2D) visualization method; positron emission particle tracking (PEPT)[24]; and MRI.[25] PIV, which can be used to track the motion of individual particles in a granular bed at exposed surfaces, yields instantaneous and mean velocity fields, as well as fluctuations of velocities up to several thousand Hertz. Compared to PEPT, the main disadvantage of the PIV technique is that it is limited to 2D measurements for opaque granular materials. Nevertheless, information collected from PIV can be used to develop an understanding of the behavior of wet granular material in an agitated blender. In earlier work, the capabilities of PIV were illustrated for the characterization of dry granular materials.[22,23,26]

The focus of this study is the characterization of the flow field of a wet material in an agitated blender using PIV. As mentioned, PIV allows velocity measurements only at exposed surfaces (2D characterization). For transparent blenders (such as glass-walled reactors), these are the free surface and the outer walls. Clearly, the understanding of how wet particles flow at the surface and near the wall is important for several granular processes (such as wet granulation and contact drying). This type of information can be used as a basis for comparison with studies involving mathematical modeling [distinct element method (DEM) simulation of wet materials in agitated blenders] or other types of measurement techniques (such as PEPT). Our findings are anticipated to have practical applications for process design and sampling procedures. The results can also be used to understand and anticipate the physical transformation (particle attrition and agglomeration) that wet solid materials can undergo in granular processes when shear is applied (granulation, wet milling, agitated drying). The paper is organized as follows. In the Experimental Setup section we describe the setup and the PIV technique. In the Results section, we first determine velocity fields at exposed surfaces for nearly monodisperse dry materials. Next, we characterize particle trajectories and describe the observed mixing patterns when moisture is added to the granular bed. The main results of this work are summarized in the final section.

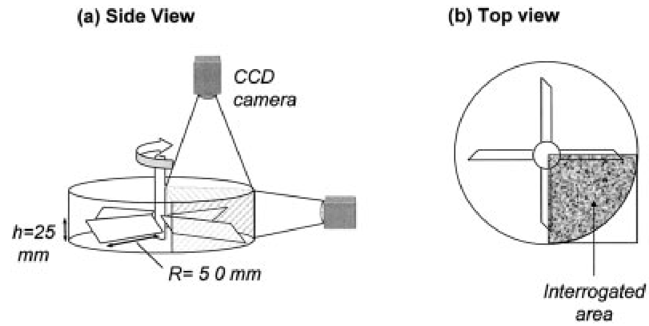

Figure 1. Four-blade agitated bed geometry.

Hatched regions are interrogated by PIV. Pitched blades viewed end-on, through outer wall: (a) side view; (b) top view. Arrow shows direction of blade movement.

Experimental Setup

Apparatus

The geometry of the bladed mixer system is shown in Figure 1. The vessel is an 800-mL glass vessel with an inner diameter of 10 cm. The upper surface of the bed is unconfined and is free to deform as a result of the action of the agitator blades. We use a *pitched*-blade agitator typical of industrial applications. Four 45° pitched blades of 25 mm width, equally spaced around the agitator shaft, impart azimuthal, axial, and radial velocities to particles in the bed. The blades are made of polyethylene and screwed to a mild steel shaft. The granular material is loaded in the cylindrical vessel to an initial depth of 25 mm, which is sufficient to totally cover the agitator blades. The agitator can be driven forward and backward using a speed controller with an accuracy of ± 0.1 rpm under load. There is an approximately 1- to 2-mm clearance between the bottom of the blades and the base of the container, and a 5-mm gap between the outer edges of the blades and the vertical vessel walls. Using a small spraying device, moisture (water in this case) is added at different points of the free surface. To ensure a good distribution of the moisture within the granular bed, PIV measurements are taken after a period of bed premixing. After several tests, we found that reproducible results can be obtained, when the bed is premixed for 5 min at an agitation speed of 50 rpm. To aid the visualization and the PIV analysis, dry art sand, containing light and dark grains, with an average diameter between 355 and 425 μm, is used. The differently colored grains are mechanically identical, that is, they have the same density, particle size, and shape. The use of art sand is motivated by the fact that it easily forms wet agglomerates. Similar behavior is often encountered with wet materials in agitated processes (such as wet granulation, drying).

PIV measurements

In our work, a CCD (charge-coupled detector) camera with a spatial resolution of 0.15 mm/pixel was placed directly above one quadrant of the flow (Figure 1a) and used to record images of the free surface at 500 frames per second (fps). The image spans an entire quadrant of the container. This high frequency of recording is needed to produce good quality data. The current PIV system allows recording a total of only 1000 contiguous frames, with a frequency up to 500 fps; at 500 fps this leads to 2 s of data. At this point, the 2 s of data can be saved and then another 2 s of contiguous data can be obtained. In principle, one can put the 2-s data sets together into one large data set. However, this is not ideal in our view, so we used a maximum of 2 s for data analysis. A second camera location enables images to be taken through transparent sidewalls (Figure 1a). However, when the moisture content exceeds 2% by mass, granular material building up at the wall prevents accurate measurements. Sequential images are processed using cross-correlation and a 3×3 interrogation cell-smoothing filter (Dantec Dynamics Inc., Mahwah, NJ). Mean velocity fields are obtained by averaging over a maximum of 1000 frames.

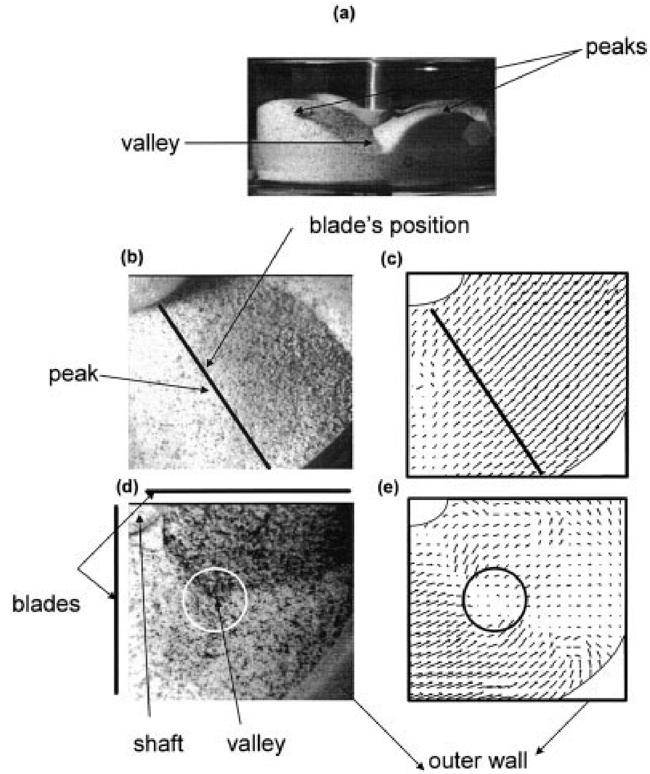

Figure 2. Instantaneous views of the agitated mixer.

(a) Side view of "peaks " and "valley "; (b) at 50 rpm, image of "peak, " with blade captured in the diagonal position; (c) corresponding PIV velocity vectors; (d) at 50 rpm, image of "valley " (blade outside the interrogated area); (e) corresponding PIV velocity vectors indicating particle recirculation.

Results

Characterization of particle flow of dry materials

Initially, the flow structure of a dry material at the free surface was analyzed. In all the experiments the agitation speed was varied between 10 and 50 rpm, which corresponds to a Froude number between 0.011 and 0.274. The impeller was rotated counterclockwise (and under the conditions we considered, no significant changes were found when the direction of rotation was reversed). To define the flow regime, we calculated the dimensionless shear rate $\gamma°*$ using the expression of Tardos et al.[27] $\gamma°* = \gamma(d_p/g)^{1/2}$, where γ is the shear rate, d_p is the bed depth, and g is gravitational acceleration. In our experiments the dimensionless shear rate $\gamma°*$ varied between 0.07 and 0.33, which corresponds to the "slow to intermediate" regime.[27] This regime is essentially dominated by sustained particle contacts.

First, we analyzed the instantaneous velocity data provided by the PIV system, as well as the corresponding footage taken by the CCD camera. Typical instantaneous measurements taken at the free surface are shown in Figure 2. A side view of the glass cylinder (Figure 2a) shows that the free surface of the granular bed deforms and rises at the position of the blade and falls between blade passes. This behavior can also be seen in the snapshots taken at the free surface (Figures 2b and 2d), which show the formation of a peak (Figure 2b) and a valley (Figure 2d), as the impeller moves through the interrogated area. The instantaneous velocities (in the plane perpendicular to the shaft) reveal that the particle motion in front of the blade (which corresponds to the position of the peak) is unidirectional, dominated by the angular rotation of the impeller (Figure 2c). However, the particles located in the wake of the blade move backward (Figure 2e).

Close examination of particle motion on each side of the peak (that is, each side of the blade) reveals that the particles at the top layer move faster than the rest of the bed and that their motion occurs through surface avalanching. A coarse estimation of the avalanches frequency was made from the video and was found to be around 10 Hz (up to three times the frequency of the blade). The corresponding video footage shows that the solid material between the two blades flows down in three planes, as can be seen in Figure 2d. One slope forms as an immediate consequence of the material accumulating at the wall. The two other planes are formed as a result of the proximity of the two blades. The wake of the leading blade (that is, particles moving backward) collides with the "push" of the following blade (that is, particles flowing forward). The three slopes intersect at a single point, which act as a material sink—a point at which particles collect with no accumulation of the granular material (circled area in Figure 2d). The surface velocity near this point (circled area in Figure 2e) is close to zero. The fact that no accumulation occurs at a zero surface velocity suggests that near this region solid particles are flowing downward, indicating the existence of three-dimensional (3D) structures within the moving bed.

Figure 3 shows velocity vs. time profiles taken at 50 rpm at a point located at the center of the PIV images, midway between the center of the mixer and the outer wall (circles in Figures 2d and 2e). At each point the velocity vector is projected along the radial and tangential direction. Figures 3a and 3b show the angular and radial component of the planar velocity. Although it appears that the particle motion is dominated by the angular rotation of the blades (the amplitude of the velocity in the tangential direction is at least two times higher than the radial amplitude), both components fluctuate with a period of about 0.3 s, essentially the period of the passing blade at 50 rpm. An examination of the video stream reveals that every time the particles are on the top of the blade, the tangential component of the velocity is at its maximum, whereas when they are located midway between two blades the velocity is at its minimum value. Figure 3 also shows that, at a given time, the radial velocity has positive values when the tangential component is below zero. This suggests that radial particle motion toward the wall occurs at times in which particles are moving backward (that is, particles are falling behind the blade). Also, when the radial velocity is integrated over time, the net flow appears to be slightly negative, which indicates that overall, the granular material at this point at the free surface has a tendency to move toward the shaft.

To determine the minimum time required to conduct proper time-averaging for the evaluation of average particle velocities, we performed a discrete Fourier transform (DFT) on 2 s of data, with a sampling time of 0.01 s. The full data set, all the way to 50 Hz, is plotted to allow for all experimental modes to

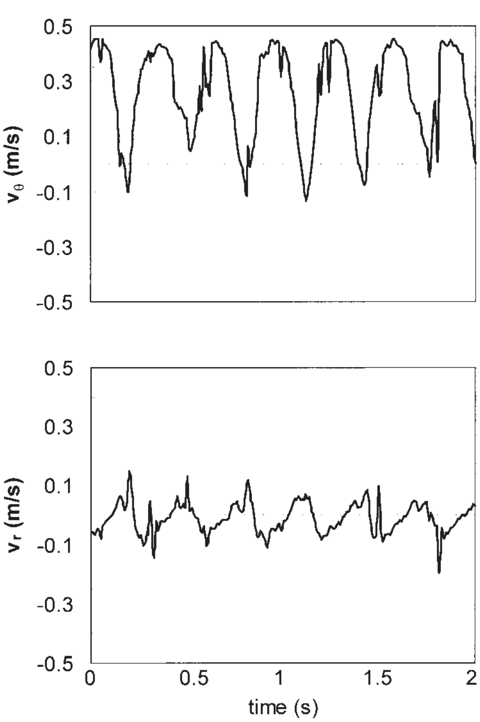

Figure 3. Variation of velocity with time at 50 rpm at a point located at the center of Figures 2d.

(i) Tangential velocity v_θ (m/s); (ii) radial velocity v_r (m/s).

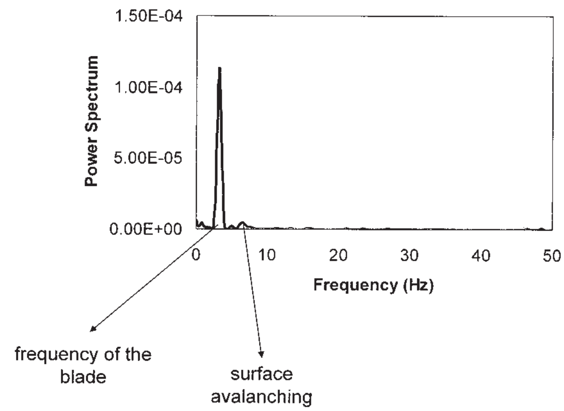

Figure 4. Power spectrum analysis of tangential velocity fluctuations at a point located at the center of Figure 2d at an agitation speed of 50 rpm.

be ascertained (Figure 4). This analysis is applied only to the tangential component because this is the primary flow direction, as indicated in Figure 3. The DFT analysis reveals the existence of a main frequency between 2.35 and 3.9 Hz, which corresponds to a 0.26- to 0.4-s time period (the maximum frequency is at 3.1 Hz, that is, a time period of 0.32 s). Therefore, this value is close to the frequency of the blade passes, as already discussed in Figure 3. Peaks of very small intensities are also shown at high frequencies, which are characteristic of the avalanching of the particles at the free surface. The intensity of the peaks suggests that surface avalanching is not a dominant characteristic when the material is dry.

The average velocity profiles at the free surface are shown in Figure 5. At each point of the interrogated area, the average velocity is obtained by averaging over 1000 frames, which corresponds to 2 s of real-time data (see Figure 5). Averaging the velocity entirely suppresses the flow structure that could be seen in Figure 3. Figure 5 clearly confirms that, on average, the particle motion at the top layer of the bed is dominated by the angular rotation of the impeller. The highest average velocities are obtained far from the shaft. Figure 5 also shows the variation of the granular temperature given by $T = ½\langle \boldsymbol{u}'\boldsymbol{u}' \rangle$. The granular temperature T is computed over a domain d_v of 0.45×0.45 mm and with a temporal resolution of 20 ms. Initial computations show that the granular temperature measured over 2 s of data is not symmetric in the azimuthal direction.

To overcome this limitation, the data obtained for a period of 2 s were averaged in the azimuthal direction. At any given time, the granular temperature at a point is a function of the fluctuation velocity $\boldsymbol{u}'$, which is the instantaneous deviation from the mean velocity and is computed over all particles contained in a subvolume d_v around the point being examined. $\langle \cdot \rangle$ denotes temporal averaging of the product $\boldsymbol{u}'\boldsymbol{u}'$. It can be expected that if the considered subvolume encompasses an ensemble of particles moving at the same velocity, which can be the case of wet agglomerates, the fluctuations will approach zero, leading to very small values of the granular temperature. The top view of the bed (Figure 5) indicates that surface fluctuations are higher far from the shaft, which corresponds to the locations where the average velocity is highest. Similar behavior has been observed in a previous study dealing with only the flow and segregation of dry material in an identical

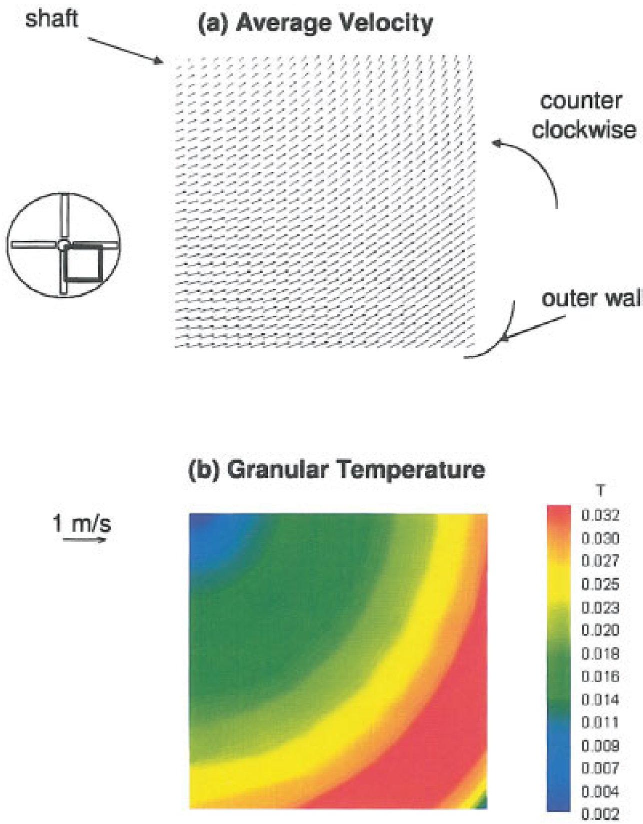

Figure 5. Average velocity vectors and granular temperature fields at 50 rpm.

Schematic shows location of image area: (a) average velocity; (b) azimuthally averaged granular temperature. Fields obtained by PIV from cross-correlation of 1000 frames, taken 2 ms apart (the interrogated area is slightly smaller than that in Figure 2). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

geometry.[26] It is important to mention that PIV data recorded near the wall for a period of 2 s reveal that the averaging time needs to be extended for both the velocity and granular temperature. In addition carrying out measurements with wet material at the transparent sidewall is problematic: when the moisture content exceeds 2% by mass, granular material builds up at the wall and measurements cannot be carried out.

Flow characterization for wet materials

The addition of moisture to the granular bed adds to the complexity of the system. One immediate consequence is the increase of cohesive forces within the bed arising from liquid bridges that form between two or more solid particles. To capture the most important features of the granular bed in the presence of moisture, we make use of image analysis and PIV measurements at the exposed surfaces of the glassed vessel. High-speed videos are taken at the top layer of the bed at different agitation speeds and moisture contents. Under the conditions of our experiments—that is, 10 rpm $< N <$ 50 rpm and 0% $< X <$ 4%, where N is the agitation speed and X is the moisture content in grams of moisture/gram dry solid—two flow regimes can be identified: (1) a *granular* regime and (2) a *correlated* regime. Similar flow regimes were identified by Tegzes et al.[28] when they studied the dynamics of avalanching of wet granular material in rotating drums. We find that in the granular regime, which is observed at very low moisture content (<0.5%), the particles behave as if they were dry and the granular flow is dominated by the motion of the individual grains. As a response to the impeller rotation, the free surface of the granular bed deforms as if the material were dry, by forming a heap where the blades are present. On each side of the heap (in front of the blade and in its wake), the free surface of the granular bed remains flat. At low moisture content (<0.5%), the cohesive forces are weak and the solid particles can freely roll down each side of the heap, smoothing out the surface. The correlated regime occurs when the moisture content is >0.5%. Under such conditions, the bed becomes more cohesive, thus preventing individual grains from moving separately. As can be seen in Figure 6, the free surface of the granular bed exhibits significant curvature as the granular material flows in the form of separated clumps or agglomerates, leading to surface roughness and regions of high porosity.

We used PIV measurements to characterize the variation of the radial and tangential velocities at the free surface as moisture is added to the system. The interrogated area is identical to the dry case (see Figure 1). Figure 7 shows these variations at a point located midway between the shaft and the outer wall. This figure exhibits several features that suggest a change in dynamics, indicative of the different regimes previously described. At low moisture content (0.5%, Figure 7b), the velocity components display several similarities to the dry case (Figure 7a), which indicates that for this liquid level the flow is dominated by the motion of individual grains. For example, the tangential component passes through maxima and minima, which correspond to the position of the particles with respect to the blades. When the wet material is on top of the blade, the velocity is at its maximum, and is at a minimum (close to zero in this case) when particles are located midway between two blades. However, both components show a large number of fluctuations with frequencies higher than that of the blade rotation. Examination of the video footage reveals that these frequencies correspond to the surface avalanching of wet agglomerates. At such moisture content, the size of the agglomerates is comparable to the size of the individual particles. The fact that surface avalanching affects the top-layer velocity profile, even though the overall flow is similar to the dry material, suggests that it is possible to characterize the onset of the correlated regime. As can be seen, the high frequencies become more significant as the moisture content is increased to 2%, which clearly indicates that the flow of wet agglomerates becomes dominant. At higher moisture content (4%, Figure 7d) the intensity of these frequencies becomes as large as the intensity of blade rotation.

To support this finding, we performed a discrete Fourier transform (DFT) analysis on the different tangential components. Figure 8 shows the power spectrum of different frequencies for different moisture contents. The graph shows that below 2%, the main frequency of oscillations is 3.1 Hz, which is close to the frequency of blade rotation. At the same time, it can be seen that the intensity of the peak decreases with moisture content, whereas other peaks appear at higher frequencies, which confirms that wet agglomerates can be detected, even under conditions where the flow of the wet materials is still dictated by the rotation of the impeller. At 4%, the intensity of the peak at 3.1 Hz

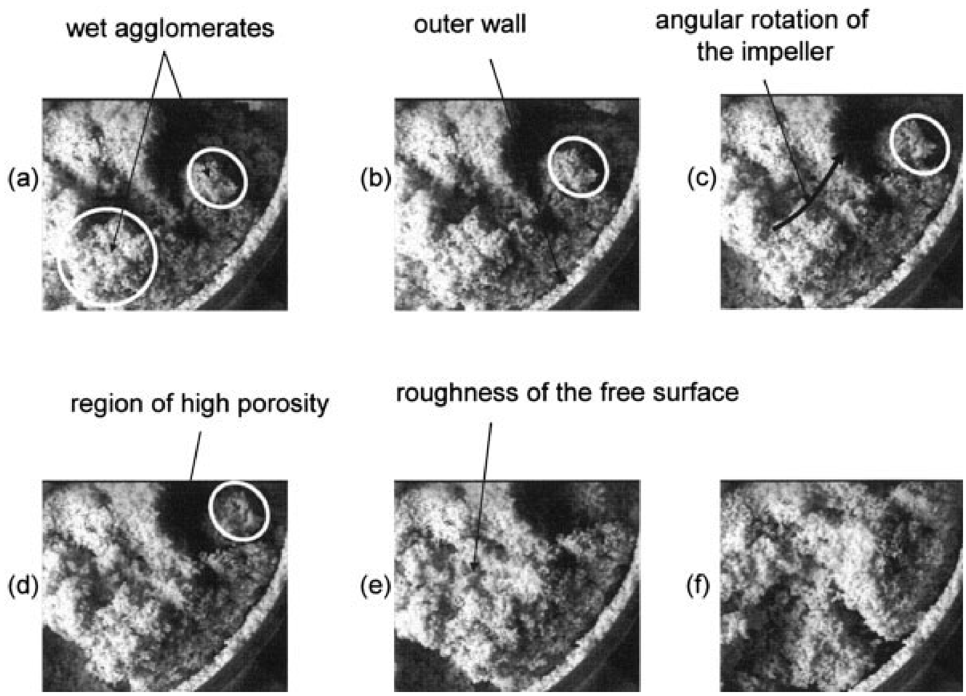

Figure 6. Top view of wet agglomerates at the free surface in the correlated regime.

Time increases from snapshot (a) to (f). Agitation speed of 50 rpm and moisture content of 2%.

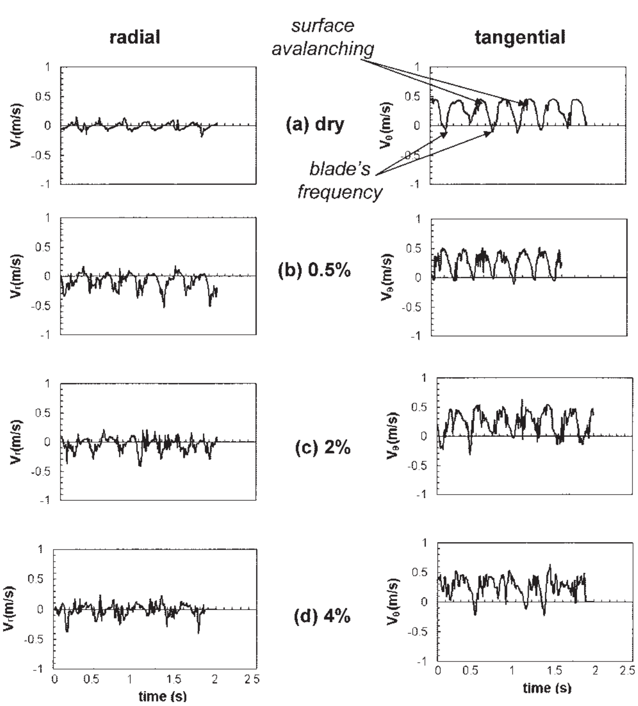

Figure 7. Variation of velocity with time and moisture content at 50 rpm at a point located at the center of Figure 6.

(a) Dry bed; (b) 0.5%; (c) 2%; and (d) 4%.

is substantially reduced and the intensity of secondary peaks (higher frequencies) is of the same order of magnitude.

In addition to the increase of surface avalanching of wet agglomerates, we found that the onset of the correlated regime is accompanied by an increase in bed porosity. The dilation of granular material under the effect of shear is a well-known phenomenon, which has been extensively studied for dry granular materials, beginning with works by Reynolds.[29] However,

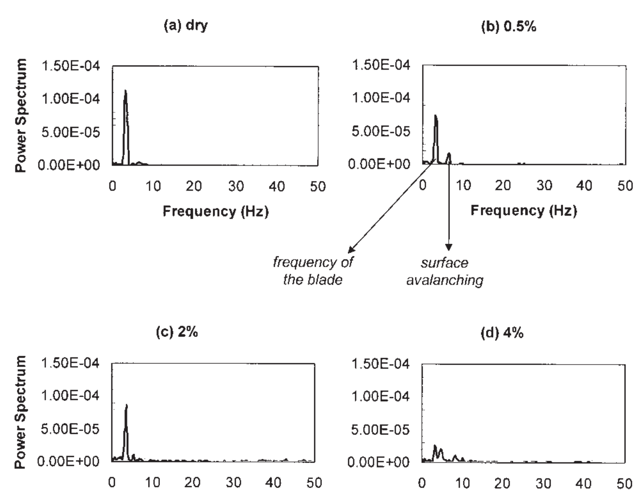

Figure 8. Power spectra of tangential velocity fluctuations at a point located midway between the shaft and the outer wall.

Effect of moisture content at 50 rpm: (a) dry; (b) 0.5%; (c) 2%; and (d) 4%.

with the exception of a few papers (see, for example, the paper by Geminard et al.[30] and references therein), the characterization of the dilation of sheared wet granular material is still an open question. In this work we concentrate only on the variation of the maximum height of the bed to quantify the variation of bed dilation in the presence of moisture (that is, we do not examine all the curvatures and surface deformation). This type of analysis provides an *integral measure* of the dilation of the granular bed. To allow a consistent comparison between the different experiments, in each case the maximum height is normalized by the initial height at rest:

$$h_r = (h - h_0)/h_0 \tag{1}$$

where h is the maximum height of the free surface for given conditions and h_0 is the initial height. All experiments are started from the same initial bed height (about 25 mm at rest). Figure 9, which illustrates the variation of the reduced height h_r with the moisture content, shows that h_r continuously increases to reach a plateau at $h_r = 0.65$. At a given shear rate, when the granular bed is dry or slightly wet (granular regime), the solid particles (which can freely flow) slide over each other, thus resulting in a slight increase in the bed volume (Figure 10a). The addition of moisture to the granular bed increases the cohesive forces leading to the formation of agglomerates, which can also roll over each other under the effect of shear. In comparison with the dry case, the interstitial volume between the agglomerates is larger (Figure 10b), eventually leading to an increase in bed porosity. The lack of dependency of h_r on the agitation speed suggests that the bed expansion is controlled by the cohesive forces, and that at the examined speeds the effect of agitation is not significant. Under these conditions, the applied shear does not appear to be sufficient to overcome the effect of cohesive forces. Such an effect is expected to be less pronounced in large-scale equipment. Indeed, Geminard et al.[30] showed that the dilation of a wet layer of granular material decreases with an increase of the normal stresses, which in practice is equivalent to increasing the mass or thickness of the granular layer.

As for the dry case, we also compute the average velocity at the exposed surfaces, and we find that for all cases the average flow at the top layer of the bed is controlled by the angular rotation of the impeller. For a better characterization of the effect of moisture on the average velocity profile, at the top

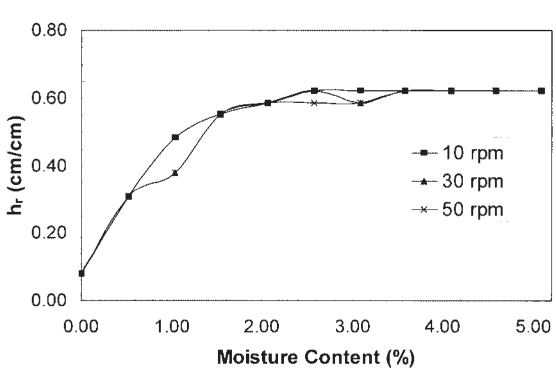

Figure 9. Variation of the maximum reduced height with moisture content and agitation speed.

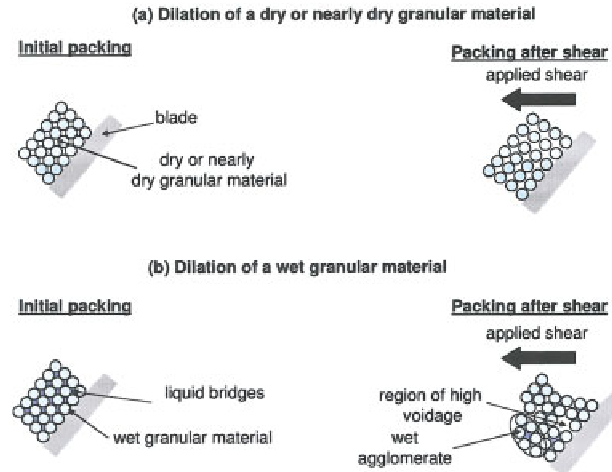

Figure 10. Dilation of granular material.

(a) Dry or nearly dry granular material (moisture content < 0.5%); (b) wet granular material (moisture content > 0.5%). The dilation mechanisms in (a) and (b) are proposed following the observed behaviors in Figures 2 and 6. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

layer of the bed, we compute the average deviation velocity profile according to

$$\mathbf{V}_{\text{dev,av}} = \mathbf{V}_{\text{wet,av}} - \mathbf{V}_{\text{dry,av}} \tag{2}$$

where $\mathbf{V}_{\text{wet,av}}$ is the 2D average velocity vector measured at a given point and moisture content and $\mathbf{V}_{\text{dry,av}}$ is the time-averaged velocity vector at the same point for zero moisture content. The vector plot in Figure 11 shows the average deviation velocity vectors for three moisture contents: 0.5, 2, and 4%. Magnitudes of the deviation vectors were computed for these moisture contents and it was found that the recording time of 2 s produces plots that slightly deviate from symmetry, indicating that 2 s of data can generate reasonably well averaged (long-time average) velocity vectors. At a moisture content of 0.5% (Figure 11a), most of the deviation velocity vectors exhibit a negative tangential component, whereas the radial component is close to zero. This indicates that the addition of small amounts of moisture to the granular bed leads to a deceleration of the wet particles in the tangential direction, whereas the radial velocity remains almost unchanged. It can also be seen that the deviation velocity becomes larger closer to the outer wall. The decrease in particle velocity (for the wet case) in this region can be attributed to an increase of wall friction with the addition of moisture. Figures 11b and 11c show that this behavior is more pronounced with the further addition of moisture. As moisture is added to the granular bed, two physical phenomena influencing particle motion and velocity profile take place: (1) the dilation of the bed (as discussed in Figure 10) and (2) formation of liquid bridging. The dilation of the bed weakens the interlocking between the particles and reduces the internal friction. Under the effect of dilation only, the velocity of the solid particles should increase. However, the liquid bridging has the effect of increasing normal stresses at contact points between particles, thus increasing friction. The increase of internal friction for wet materials was

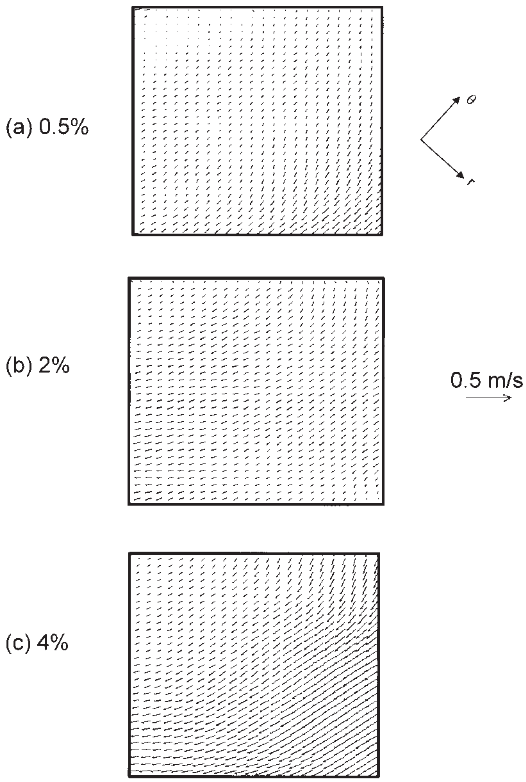

Figure 11. Variation of the average deviation velocity V_{dev} with the moisture content at 50 rpm.

(a) 0.5%, (b) 2%; and (c) 4%. At each point, V_{dev} is the average velocity for a given moisture content minus the average velocity for the dry material.

discussed in a recent paper by Moore and Iverson.[31] The results in Figure 11 suggest that the effect of liquid bridging on the velocity field dominates over dilation. It can be expected that with further increase in moisture content the volume of the liquid bridges becomes important and the distance between the particles increases. Under these conditions, the interstitial liquid plays the role of a lubricant, thereby reducing the internal friction.

It becomes clear from the above discussion that the dynamics of wet granular material is affected by the cohesive forces that arise in consequence of the presence of moisture. Another way to quantify the role of moisture on a dry granular material is to examine the variation of fluctuational velocity, that is, the granular temperature as moisture is added to the granular bed. The changes in granular temperature at the free surface with moisture content are shown in Figure 12 for a velocity of 50 rpm. As before, the data for the granular temperature are averaged in the azimuthal direction. For the dry case, Figure 12a shows that the granular temperature is highest far from the shaft. Figures 12b to 12d clearly show that the granular temperature at the top layer of the bed is considerably reduced when moisture is added to the system. This is true even when a very small amount of moisture is added (as small as 0.5%). This trend has been confirmed for other agitation speeds (10 and 30 rpm) as well. This effect can be understood because within agglomerates that form as a result of cohesive forces local velocity fluctuations are substantially reduced, and thus the granular temperature at a given point will approach zero. This behavior reflects the stabilizing role that moisture can play in agitated granular beds, even when small amounts of moisture are involved.

Summary and Conclusions

In this study, we used a PIV technique (2D measurement) to characterize the flow pattern and velocity fields of nearly monodisperse dry and wet materials in a cylindrical glass vessel, equipped with a four-pitched blade impeller. The configuration considered in this study is relevant to several granular processes encountered in industry (such as granulation and filter bed drying). For the dry case, we found that as a response to the impeller rotation, the free surface of the bed deforms, by rising where the blades are present and by falling between blades, causing the solid particles to recirculate. Examination of instantaneous velocity fields shows that the particles in front of the blade move forward, whereas particles behind it flow downward. When we averaged the flow, we found that the overall particle motion is dominated by the angular motion of the impeller. This fact has been confirmed by a DFT analysis, which reveals the existence of a dominant frequency at 3.125 Hz, close to the frequency of blade passes.

When moisture is added to the granular bed the particle motion changes from a regime where the flow of individual grains dominates to a regime where the flow is controlled by the motion of agglomerates that form as a result of cohesive forces arising from liquid bridging. Analysis of the velocity time profile for several moisture contents shows evidence of a switch in behavior as moisture is added. In fact, it was observed that at low moisture content (granular regime) fluctuations of high frequencies and small intensities are superimposed on the flow, which is dominated by the angular rotation of the impeller. These fluctuations were attributed to surface avalanching of the wet agglomerates at the top layer of the bed. With the increase of moisture content (correlated regime), the intensity of these fluctuations became significant, which are of the same order of magnitude as the intensity of the fluctuation corresponding to blade passes. This behavior was confirmed by DFT analysis performed on the tangential velocity (dominant flow). It was found that at low moisture content the power spectrum exhibits one main peak corresponding to the frequency of impeller rotation, whereas at high moisture content several peaks of equivalent intensities can be identified at different frequencies.

The change in flow dynamics also reflects on the average velocity. PIV measurements showed that the average velocity decreases with moisture content. This behavior was attributed to an increase of internal friction resulting from cohesive forces. The fact that the granular medium becomes more cohesive prevents particles from moving individually, thereby reducing the fluctuation of velocity, which translates into a sharp decrease in granular temperature. The addition of moisture not only affects the flow dynamics, but it also changes the structure of the granular bed. In particular, it was found that because of the dominance of cohesive forces over shear forces, the porosity of the bed was substantially increased. Such large variations in bed porosity can have significant consequences for product uniformity and quality, given that

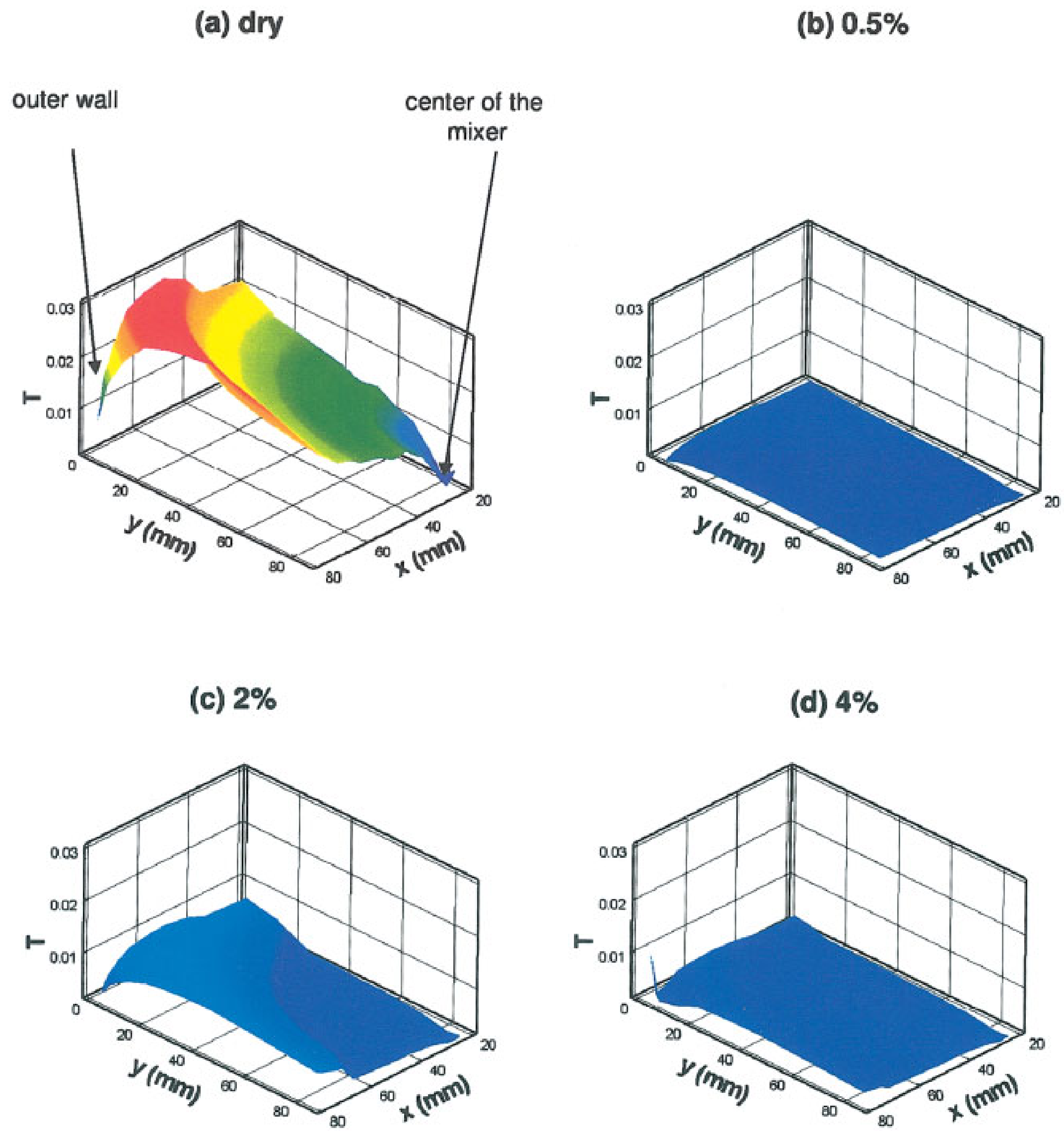

Figure 12. Variation of the azimuthally averaged granular temperature at the free surface with the moisture content at 50 rpm.

(a) Dry bed; (b) 0.5%; (c) 2%; and (d) 4%. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

regions of high and low solid densities can coexist within a blender.

Although the present study has unveiled several fundamental features of wet granular materials in agitated blenders, future studies should focus on the role of the cohesive forces. This can be done by testing different liquid solvents with different physical properties. Surface tension and viscosity of the liquid are of particular interest. Before a complete understanding of the behavior of wet granular material can be reached, a 3D characterization of flow structures within the granular bed is necessary. At this stage, it remains to be seen whether characterization techniques used for dry materials, such as PEPT,[32] can be directly used, when moisture is added to the granular material. This is a necessary step toward developing computational tools that can reliably describe the flow of wet granular materials.

Acknowledgments

This work was partially supported by the National Science Foundation, American Chemical Society–Petroleum Research Fund, and Bristol-Myers Squibb.

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Manuscript received July 14, 2005, and revision received Mar. 13, 2006.