Scale-up effects on flow patterns in the high shear mixing of cohesive powders

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Abstract
Processing of granular material often requires mixing steps in order to blend cohesive powders, distribute viscous liquids into powder beds or create agglomerates from a wet powder mass. For this reason, using bladed, high-speed mixers is frequently considered a good solution by many types of industry. However, despite the importance of such mixers in powder processing, the granular flow behavior inside the mixer bowl is generally not totally understood. In this work extensive experimentation was performed comparing the behavior of a lab-scale mixer (1.9 l vessel volume) to that of a pilot-scale mixer (65 l vessel volume) with a mixture of some pharmaceutical excipients (e.g. lactose, cellulose). The aim was to propose a new and more detailed method for describing the complex powder rheology inside an high shear mixer using impeller torque, current consumption and particle image velocimetry (PIV) analysis. Particularly, a new dimensionless torque number is proposed for the torque profile analysis in order to isolate the contributions of mass fill and blade clearance at the vessel base. Impeller torque and motor current consumption were integrated with PIV to obtain more detailed information about the surface velocity and flow pattern changes in the pilot-scale mixer. Mass fill resulted to be one of the most critical variables, as predicted by the torque model, strongly affecting the powder flow patterns. An additional mixing regimes was furthermore defined according to the observation of the surface velocity of the powder bed.

Keywords: high shear mixer, cohesive powders, scale-up, mixing regimes

1 Introduction
High shear mixers, also known as high intensity mixers (Paul et al., 2003), are widely used for the powder processing. They can be used for simple mixing, in particular of cohesive materials, since they exert a high local shear on the powder which breaks down the small aggregates (Harnby, 1997), or for more complex operations which involve both solids and liquids. For example in a wet granulation process, a high shear mixer can promote a good liquid dispersion and proper consolidation of the product, in order to obtain aggregates with useful structural forms, improved flow properties and reduced segregation propensity (Litster et al., 2004). They are constituted by a bowl and a centrally mounted impeller rotating about a vertical or an horizontal axis. For the case
with vertical axis, which is studied presently, the impeller can be top- or bottom-driven. Despite the importance of this type of mixers in many industrial processes (Knight et al., 2001), the granular flow behaviour inside the vessel (i.e. how the motion of the powder within the mixer is induced by the impeller) is currently not totally understood. Different techniques have been used in order to carry out a description of the powder flow within the mixer. Techniques such as positron emission particle tracking (PEPT) and particle imaging velocimetry (PIV) give a direct visualization of the flow patterns within the bulk of powder and at the boundaries (typically the free surface) respectively. Also other experimental methods such as thermal tracer method (Saberian, 2002) or simulation techniques such as the discrete element method (DEM) (Stewart et al., 2001, Chandratilleke et al., 2010, 2012, Radl et al., 2012, Remy et al., 2010) have been used with the aim of observing and understanding the internal flow patterns in powder mixing. PEPT technique (Wellm, 1997) and high-speed imaging (Litster et al., 2002, Nilpawar et al., 2006) in particular both confirmed that the powder mass within the vessel can exhibit a toroidal vortex motion consisting in an outward motion in the lower regions of the mixer and an inward motion in the upper regions, with lifting at the wall and falling close to the axis of the mixer (Salman et al., 2007). However results obtained with high speed imaging by Plank et al. (2003) suggest that the powder bed dynamics can be more complex. Authors have found that small increases in fill level can significantly decrease the powder velocity at the surface. At large scale mixers, they have observed that the surface was stagnant approximately 1/3 of each impeller revolution.

Amperage as well as motor power consumption, impeller torque and motor slip have been frequently monitored as indirect effects of the mixing process on the mixer. Particularly, power consumption and impeller torque have been used to identify how the flow patterns in a mixer depend on the geometric configuration (impeller shape as well as bowl shape) and the impeller speed (e.g. Paul et al., 2003; Dareliusa et al., 2007). In particular Knight et al. (2001) developed a model for predicting impeller torque in a high shear mixer. They represented the effect of the mass of powder $M$ and the bowl radius $R$ using a dimensionless torque group $T/MgR$ as a function of the impeller Froude number and changed several operating conditions: impeller geometry, impeller shape, mass fill, bowl diameter, impeller clearance and powder size distribution. They obtained a good correlation between the proposed model and the experimental data.

The geometrical similitude has been frequently identified as an essential prerequisite for scaling-up powder mixers (Litster et al., 2002; Fan et al., 1990), and should be in principle the first to be assured among kinematic and dynamic ones. The design of industrial mixers nevertheless varies from manufacturer to manufacturer and might present differences in bowl proportions and impeller shape at different scales (i.e. variations in blade angle and shape of the blades). Also filling level of the bowl should be scaled according to geometric rules. However, while the quantity of material processed at the laboratory stage usually tends to be minimized in order to reduce wastes and costs, at industrial level it is maximized in order to increase the productivity (Litster et al., 2002). In practice, the geometric similitude is seldom fully respected. Also the high-shear mixers used in the present research were not geometrically similar. The shape of the small-scale bowl was a little bit more smoothed in the bottom border (i.e. close to the impeller tip), thus small-scale blades were slightly more curved. Moreover small-scale mixer was top-driven, while pilot-scale was bottom-driven. On the other hand, blade angle was similar for both mixer scales. In the literature the behavior of free-flowing (Knight et al., 2001) or idealized (spherical) materials (Radl et al., 2012) is often studied for sake of simplicity. Here an industrial mixture of cohesive powders was used.
The aim of this work was to propose a more detailed model for the prediction of torque in a high shear mixing process of cohesive powders by introducing a modified dimensionless torque number as a function of the impeller Froude number and taking into account of the filling ratio of the vessel and the impeller clearance at the vessel base, i.e. the distance from bottom wall of the bowl. Among all the operating variables, mass fill resulted to be one of the most critical parameters for choosing the mixing patterns and shear energy (Paul et al., 2003, Landin et al., 1996a,b) and for the characteristics of the final products (Mangwandi et al., 2011). Predicting torque with higher level of precision can be useful not only because torque quantifies the power required by the motor to move the impeller (i.e. useful for design purposes), but also because it is strongly related to the flow patterns and the motion regimes of the material within the vessel which impact on the mixing efficiency. The new dimensionless number clearly isolated the contribution of the mass fill and the blade clearance at the vessel base. Our own experiments and literature data by Knight et al. (2001) have been used in order to validate the new model, to give a physical meaning to the parameters and to better characterize the flow pattern inside the mixer.

2 Materials and methods

Experiments were performed using a bench-scale and a pilot-scale mixer. The bench-scale mixer (MiPro, 1900 ml vessel volume, ProCepT, Zelzate, Belgium) was top driven (Figure 1) and the pilot-scale mixer (Aeromatic Fielder PMA 65 L, Eastleigh, Hampshire, UK) was bottom driven (Figure 2). Both of the mixers had stainless steel vessels and three bladed impellers. Impeller blade angle was about 30° for both of them.

![Figure 1. Schematic of the bench-scale mixer. Impeller is three bladed, top-driven and equipped with a torque measurement and registration system.](image-url)

The bench-scale mixer was equipped for measuring the impeller torque while the pilot-scale mixer for measuring the motor current values. A mixture of some pharmaceutical excipients was used: lactose monohydrate 150 mesh, 73.5% w/w (Lactochem Regular Powder 150 M, Friesland Foods, Zwolte, The Netherlands), microcrystalline cellulose (MCC), 20% w/w (Pharmacel 101, DMV International, Veghel, The Netherlands), hydroxypropylmethylcellulose (HPMC), 5% w/w
(Pharmacoat 603/Methocel E5, Shin-Etsu Chemicals, Niigata, Japan) and croscarmellose sodium, 1.5% w/w (Ac-Di-Sol, FMC Biopolymer, Philadelphia, USA). The mass fill was varied between 20% and 40% for both the mixers.

Figure 2. Schematic of the pilot-scale mixer: (a) location of the high speed CCD camera and (b) coordinate system for the surface velocity measurements tangential direction (tangential velocity) is parallel to the impeller tip speed; radial direction (radial velocity) is pointing towards the centre of the bowl and perpendicular to the impeller tip speed. The two components belong to a plane which is roughly perpendicular to the bed surface.

The impeller clearance in the bench-scale mixer was also modified adding one or more annular spacers between the bowl and the mixer closing cup which holds the impeller.

Powder flow patterns in the pilot-scale mixer was characterized by measuring the powder surface velocity. A high speed camera (FastCam PCI 1000, Photron) at 1000 fps and PIV software written in MATLAB were used. Since the surface velocity measurements for the dry mixture could not be acquired for the presence of dust, a very small amount of water (less than 2% w/w of the batch size) was added. The mixture was observed from a sampling port on the top closing cover and the high speed CCD camera was placed perpendicularly to the moving powder surface as in Figure 2a (closing cover not shown). The coordinate system chosen for the analysis is also shown in Figure 2b. 512x240 images were acquired at 200 fps. PIV was performed using the open source MATLAB toolbox MatPIV (Sveen, 2004), adopting an interrogation window shifting technique (Westerweel et al., 1997) in three steps (24x24; 24x24; 12x12) and filtering the velocity field to remove wild vectors.

3 Results and discussion

Knight et al. (2001) measured the impeller torque values during the mixing of sand of different size fractions in high shear mixers, changing the impeller blade design, rotational speed, fill and bowl size. They represented experimental data by a dimensionless torque number $T$: © 2013. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/
where \( t \) is the measured torque value (Nm), \( R \) is the bowl radius (m), \( M_{\text{tot}} \) is the bowl mass capacity (kg) and \( g \) is the gravitational constant (9.81 m s\(^{-2}\)). For best representing the results obtained using the bench-scale mixer, a new dimensionless torque number has been considered taking into account explicitly the vessel fill ratio, \( X \):

\[
T = \frac{t}{gR M_{\text{tot}} X^\beta}
\]

which is function of \( X \) but also of the new parameter \( \beta \). The parameter \( \beta \) accounts for the effect of a “static” contribution, equivalent of a static head which is not a function of the impeller speed, and a “dynamic” contribution, function of the impeller speed:

\[
\beta = \alpha_S + \alpha_D \sqrt{Fr_I}
\]

where \( \alpha_S \) and \( \alpha_D \) are two constants and \( Fr_I \) is the Froude number related to the impeller speed:

\[
Fr_I = \frac{\omega_I^2 R}{g}
\]

where \( \omega_I \) is the angular speed (rad s\(^{-1}\)) of the impeller. The introduction of \( X \) and \( Fr_I \) is one of the novelties of this study - see for comparison Eq.(1) - and accounts for the effects of the fill ratio and impeller speed on the distribution of the powder inside the vessel which changes because of the centrifugal action of impeller rotation and is expected to impact on the measured torque.

The experimental data by Knight et al. (2001) (Figure 3a) can be rescaled according to the new dimensionless group of Eq.(2) as shown in Figure 3b. The results show that the impeller torque data points can be fitted by a linear function when they are plotted in the form of the new dimensionless torque number against the square root of the impeller Froude number.

Now a static \( k_S \) and a dynamic \( k_D \) part, derived from Eq. (2) and Eq.(3), can be clearly separated as follows:

\[
T = t C \frac{1}{X^\alpha S X^\alpha D \sqrt{Fr_I}} = t C \frac{1}{k_S k_D}
\]
Figure 3. Torque profiles (a) obtained by Knight et al., (2001) for different mass fills, using a high shear mixer with a bowl diameter of 0.30 m, and (b) dependence of the new dimensionless torque number on the square root of $Fr_I$, impeller torque data presented by Knight et al., (2001).

$C$ is the slope of the master curve which depends on the bowl geometry and mass capacity.

The torque profiles obtained using the bench-scale mixer at different blade clearances at the vessel base (0.5, 2 and 4 mm) and mass fills (20, 30 and 40%) are shown in Figure 4. Each measurement was repeated at least three times and torque profiles resulted to be almost overlying for a given mass fill and blade clearance. For this reason, error bars are not visible in Figure 4 since they are completely negligible.

Figure 4. Torque profiles obtained using the bench-scale mixer at different mass fills and clearance values.

It can be seen that the fill ratio strongly affects the impeller torque value at different impeller speeds during the mixing of the dry mixture. In particular it can be noted that for low fill ratios, torque
profiles can be roughly divided into two parts. At low rotational velocity, impeller torque increases linearly with increasing the impeller speed while at higher impeller speed it tends to become constant. For larger fill ratio instead the torque slope variation is roughly constant and the increase is mostly linear. Especially when the mass fill is 20%, the break point in the torque profile corresponding to the change in slope can be clearly distinguished. The change in slope occurs at 800-900 rpm for the smallest fill ratio and seems to be delayed to higher impeller speed with increasing the fill ratio. These results slightly differ from the findings of Knight et al. (2001). They also noted that the dependence of torque on impeller speed displayed s-shaped character (i.e. decrease in torque profile slope for impeller speed higher than a critical value) but the degree of s-shaped character slightly increased with increasing the mass fill. This discrepancy might be caused by the different impeller blade design, in fact they used an impeller blade angle of 90° for the comparison between different mass fill instead of 30° blade angle used in the present work. This difference might lead to different flow patterns, thus determining different impeller torque profiles.

The break point in torque profiles in Figure 4 can be explained by considering the results presented by Litster et al. (2002). They measured the variation of powder surface velocity during the mixing of a similar granular mixture at different rotational speeds. The mixture was composed of lactose monohydrate. According to their results, two mixing regimes can be identified. At low impeller speeds, “bumping regime” was observed: powder surface remained horizontal and the bed was raised as the impeller passed underneath. At higher impeller speeds, “roping regime” was noted. The powder flow regime was determined from the well-known toroidal flow pattern and the powder bed resulted to be more expanded. The transition between the two different regimes was clearly described by the surface velocity measurements. The velocity values increased linearly with the impeller speed in the bumping regime. In the roping regime instead, surface velocities are no longer proportional to the rotational speed of the blades and tend to stabilize around a constant value. It is thus suggested that the slope variation in torque profiles in Figure 4 (i.e. break point) can represent the transition between the bumping regime and the roping regime. As a matter of fact, impeller torque represents the resistance of the powder to the mixing. Powder bed results to be more expanded during the roping regime and vertical turnover is very effective, thus the resistance exerted from the powder on the impeller blades is expected to be less influenced from the increase of rotational speed in this case. Moreover, it is suggested that the powder bed expansion can be more difficult to achieve when fill ratio is higher and more energy (i.e. higher rotational speed) might be required in order to force up the powder and obtain the transition between the two flow regimes. This phenomenon might explain the increase in the rotational speed required to determine the break point in the torque profiles when mass fill is higher, as reported in Figure 4. Similar considerations about the effects of mass fill on the achievement of the roping flow have been proposed by Litster et al. (2002) in their published work. In addition, Figure 4 shows that changes in the blade clearance determine a smaller variation in the torque profiles compared to the effects of the mass fill variation. Particularly, it can be noted that torque values tend to decrease with increasing the impeller clearance. It is suggested that increasing the impeller clearance might decrease the friction between the impeller and the bottom of the bowl. The shape of the profiles seems to be independent on the impeller clearance instead. The model proposed in Eq. (2) was then used to fit torque profiles in Figure 4. Accordingly three linear master curves were obtained: each of them represents a certain impeller clearance and summarizes the effect of the mass fill on the impeller torque value (Figure 5).
The three master curves in Figure 5 are close to each other but a certain difference in slope and intercept can be noted. A more considerable difference in slope can be observed between curves representing 4 mm and 2 mm height. Particularly, the slope of the master curve increases with increasing the impeller clearance from 2 mm to 4 mm. These results are in agreement with those presented by Knight et al. (2001), while the result for the curve representing 0.5 mm clearance slightly differs.

The effect of the variation of mass fill and impeller clearance on the static term $k_S$ can be observed in Figure 6. The static term $k_S$ distinctly depends on the impeller clearance for a given mass fill. Particularly, $k_S$ increases with increasing the impeller clearance. It can be therefore noted that the higher is the impeller clearance (i.e. impeller distance from the bottom) the weaker is the dependence of $k_S$ on the mass fill.

**Figure 5.** Dependence of the new dimensionless torque number on the square root of impeller Froude number: each of the curves represents an impeller clearance value (bench-scale mixer).

**Figure 6.** Dependence of the parameter $k_S$ in Eq. (5) on the mass fill and the impeller clearance, during mixing of dry powders at bench-scale.
As can be seen in Figure 6, $k_s$ values corresponding to the highest impeller clearance (4 mm) does not show any dependence on the mass fill. Also-the dynamic term $k_D$ is plotted and related to the square root of the impeller Froude number. Figure 7 shows the $k_D$ values and the comparison between different impeller clearances and bowl mass fills.

![Figure 7](image-url)

**Figure 7.** Dependence of the parameter $k_D$ in Eq. (5) on the square root of the impeller Froude number: effect of the mass fill $X$ and the impeller clearance during mixing of dry powders at bench-scale.

The variation of the dynamic term $k_D$ with the impeller speed mainly depends on the mass fill (see Figure 7). It is interesting to note that the slope of $k_D$ profiles tend to be higher when mass fill is lower. A higher slope in $k_D$ profile can be correlated with a sharper change in slope of torque profiles at lower impeller speed values (see Figure 4): in fact the change in slope in the torque profiles was more pronounced when mass fill was lower. As can be observed in Figure 7, any dependence of $k_D$ on the impeller clearance can be neglected, since $k_D$ profiles at different impeller clearances are almost superimposed for a given mass fill.

Mixing of the same mixture of dry powders was performed using a pilot-scale mixer as well. The results of this first analysis on impeller torque profiles at bench-scale suggested the essential importance of mass fill in determining the granular flow behaviour within the mixer bowl. For this reason, the second analysis was mainly focused on the effects of mass fill variation on the flow patterns during powder mixing using the pilot-scale mixer. As a first assumption, minimum and maximum rotational speeds of the pilot-scale mixer were chosen in order to keep the same range of impeller tip speed as in the bench-scale mixing. Thus, the range of impeller tip speed was about 2-10 m/s. The impeller tip speed $v$ was calculated using the Eq. (6):

$$v = \frac{\pi DN}{60}$$

where $N$ is the rotational speed (rpm) and $D$ is the impeller blade diameter (m) (Koller et al., 2010). Accordingly, rotational speed for the pilot-scale mixer results to be lower compared to the bench-scale mixer for a given range of impeller tip speed.
Motor current values were then measured at different rotational speeds (150-400 rpm) and for three different mass fills (20, 30 and 40%). Resulting profiles are reported in Figure 8. Even though motor current is known to be less accurate than impeller torque for monitoring mixing in bladed mixers, motor current profiles in Figure 8 are here considered as an indication of the load on the main impeller and qualitatively compared with torque profiles in Figure 4.

![Figure 8](image_url)

**Figure 8.** Motor current measurements during the mixing of dry powders with the pilot-scale mixer at different rotational speeds (150-400 rpm) and mass fill (20, 30 and 40%).

As can be easily noted from the comparison, the slope of the motor current profiles tends to decrease with increasing the rotational speed. The change in slope is not as sharp as in the torque profiles, but still each motor current profile can be ideally divided into two parts characterized by different slopes. Surface velocity measurements were therefore taken in order to get more accurate information about the powder flow behaviour and to determine how the transition between bumping and roping regime is affected by the mass fill variation during the mixing at pilot-scale. A high speed camera and particle image velocimetry (PIV) software were used. The fluctuation of surface velocity in radial and tangential directions during the measurement time and for a given rotational speed and mass fill can be effectively described by attractor plots (Figure 9).

As can be noted from the annular shape of attractors in Figure 9a, the surface movement tended to be strongly periodic: while rotating, the bed was locally raised when the impeller blade passed underneath and, as a consequence, a heap formed with the powder forced to displace from the vessel wall to the centre of the bowl. After the blade has passed, the powder bed tended to return back to its initial position. This phenomenon can be considered as a typical feature of the bumping regime and determined regular oscillations of the radial and tangential velocity components. It can be furthermore noted from the attractors plot that this oscillation decreases with increasing the rotational velocity and that the tangential component of the velocity is one order of magnitude larger than the radial one confirming observation by Remy et al. (2010).
Remy et al. (2010) performed simulation studies based on DEM of the mixing process of mono-disperse, cohesionless spheres in a bladed mixer. They found that a three dimensional recirculation convective zone develops near the front of the impeller blades for low mass fill, promoting a good vertical and radial mixing. These recirculation zones are strongly related to the heaps observed on the surface of the bed. At high mass fills, the convective zone is compressed towards the bottom of the vessel and the transport of material to the bed surface is limited. Koller et al. (2010) experimentally proved Remy et al. (2010) results by analyzing convective and diffusive properties of a binary pharmaceutical powder blend. Using NIR spectroscopy for monitoring the powder-blend composition, they demonstrated that for high fill levels diffusive mixing is prevailing and strongly reduces blending kinetics. However the simulations performed by Remy et al. (2010) were carried out at low rotational speed (10-20 rpm) and it is likewise important to study what happen at higher rotational speed.
Figure 10. Variation of surface velocity as a function of impeller rotational speed during the mixing at pilot-scale: (a) variation of mean values and (b) standard deviation.

The description made through the attractor plots can be put on a more quantitative base by plotting the averaged surface velocity and its standard deviation (Figure 10) as a function of impeller speed for the three fill levels considered.

The mean surface velocity (m/s) was calculated using the Eq. (7):

$$\bar{v} = \text{mean} \left( \sqrt{\bar{v}_r^2 + \bar{v}_\theta^2} \right)$$  \hspace{1cm} (7)

where $\bar{v}_r$ and $\bar{v}_\theta$ are the radial and tangential velocity component respectively. The standard deviation of the surface velocity was instead evaluated as:

$$\sigma = \frac{\text{mean} \left( \left[ \bar{v}_r - \text{mean}(\bar{v}_r) \right]^2 + \left[ \bar{v}_\theta - \text{mean}(\bar{v}_\theta) \right]^2 \right)^{\frac{1}{2}}}{2}$$  \hspace{1cm} (8)
As can be seen in Figure 10, mean surface velocity and standard deviation values are clearly affected not only by the impeller rotational speed but also by mass fill. Particularly with respect to mass fill, two different behaviours can be observed at 20% mass fill and at 30-40% mass fill respectively. At 20% mass fill standard deviation profile after a strong initial decrease stabilizes at a minimum value at 250 rpm. At this value of impeller speed the average velocity start to increase weakly with a sudden increase after 350 rpm. This behaviour suggests that a change in motion regime has occurred within the vessel. Powder flow is therefore likely to be more mono-directional and to follow the well-known toroidal pattern; hence the roping regime has developed. This idea is confirmed by considering the radial component of the surface velocity (Figure 11) which, at 20% mass fill, follows the same trend of the standard deviation. It decreases up to 250 rpm and then stabilizes at around a minimum value.

![Figure 11. Average radial velocities at the surface as a function of impeller speed and parametric in the mass fill (pilot-scale mixer).](image)

It is suggested therefore that the transition between bumping and roping regime can be described by a decrease of radial velocity and standard deviation values, which reach a minimum value at a critical impeller rotational speed. It can be observed also that the average radial velocity component is always positive, meaning that the surface dynamics continually leads powder from the wall to the centre of the vessel. The tangential profile was not considered in the analysis since it is qualitatively and quantitatively very similar to the mean surface velocity profile of Figure 10a (the tangential velocity is one order of magnitude larger than the radial one as can be observed in Figure 9).

At 30 and 40% mass fill the behaviour of the bed seems to deviate from the simple scheme bumping/roping regimes typical of 20% mass fill. The mean surface velocity profiles at 30 and 40% mass fill show a maximum value at around 250 rpm, then surface velocity monotonically decreases (40% mass fill) or decreases and stabilizes around a constant value (30% mass fill). As a general comment, it can be observed that the mean surface velocity increases lowering the mass fill, with exception at around 250 rpm. Also standard deviation profiles in Figure 10b show different trends. They are similar for 30 and 40% mass fill and initially decrease with increasing impeller rotational speed, then increase at 250 rpm and finally stabilizes around a minimum value after 300 rpm. The decrease of mean velocity after the transition point at higher mass fills (especially at 40% mass fill)
can be explained by considering the formation of two ideal mixing layers: a bottom layer which wraps the area surrounding the impeller, and a top layer which is poorly affected by the blade convective motion. With increasing the mass fill, the transport of powder from the bottom to the surface might be reduced, thus leading to a less effective mixing during the roping regime. This hypothesis is clearly confirmed by the observation of radial velocity component (Figure 11). It can be seen, in particular for 40% mass fill and to a minor extent also for 30% mass fill, that radial velocities becomes negative when a critical impeller speed is reached. According to the adopted convention the material on the surface moves towards the wall of the vessel, which is exactly the opposite of what happens at low velocity or low mass fill. These experiments therefore not only strengthen the conclusion of Plank et al. (2003) on the possible existence of stagnation period at the surface for high fill levels but also show the possibility of having a reversal of the flow direction at the surface. Also recent studies performed with a single blade moving in a granular bed confirmed the possibility of significant changes in the flow profile and the absolute magnitude of the velocities on the top of the particle by increasing the bed height (Radl et al, 2012). It is therefore suggested that a new regime, different from roping can progressively develop within the vessel with the formation of a two layered structure and the top layer “floating” or “surfing” over the bottom one. It is hypothesized that such top layer, characterized by a low tangential velocity (~0.1 m/s) and a negative radial velocity at the surface, may constitute a second toroidal cell rotating in opposition to that existing below. The free surface renewal as well as the overall bed renewal are expected to be poor and impact negatively on the mixing efficiency in this regime. It has to be noted also that this regime cannot be identified only by analyzing torque or motor current profiles, since they reach a plateau after the transition from bumping to roping regime.

**Figure 12.** Scheme representing the effects of mass fill and rotational speed on the transition between the different regimes observed on the pilot-scale mixer.

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All the flow patterns and mixing regimes observed in this study have been qualitatively sketched as a function of impeller speed and mass fill in Figure 12. At low rotational speed bumping regime dominates independently of the rotational speed, with convective recirculation zones in front of the blades as described by Remy et al. (2010), which determine the periodic expansion of the bed at the surface. The influence of such recirculation zones on the surface flow pattern fades down increasing the fill level. At higher rotational speed and low mass fill, the roping regime dominates with the typical toroidal flow pattern. However, increasing the mass fill, a smooth transition occurs and the bed splits in two portions: a bottom layer rotating according to the usual toroidal pattern imposed by the blades and a surface layer with a motion almost independent of that close to the blades with the material “surfing” on the top and radially rotating in opposition to the bottom layer.

4 Conclusions

The main conclusions of this work can be summarized as follow: - a model for the prediction of the impeller torque required to mix a cohesive powder mixture in a high shear mixer has been proposed; - this new model has been used to plot experimental torque values in the form of a new dimensionless torque number against the square root of the impeller Froude number; - a static term, which mainly depends on the impeller clearance, and a dynamic term, which depends on the mass fill, have been identified and their trends have been plotted against the Froude number; - this new model can be used to better explain and describe the powder flow behaviour during the high shear mixing. The model for torque prediction, developed at the bench-scale, has shown the major role played by mass fill on the flow patterns. At pilot-scale, this specific aspect has been investigated through motor current consumption and surface velocity measurements. It has been observed that while torque profile can characterize the transition between the bumping and the roping regimes, the third regime here described can be captured only by surface observation and not by torque or motor current profiles, since they both reach a plateau after the transition from bumping to roping regime. Further experiments trying to characterize the extension of the observed surface convective cells, as well as the variation in mixing efficiency due to the transition between the different regimes need to be done in the future in order to complete the understanding of this mixing process.

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