On the Relationship between Torque and Flow Structure in Powder Mixers

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Abstract

This work establishes the link between direct measurement of powder flow in a horizontal mixer and shaft torque. Three agitator designs were used: one featured six long flat blades, one a long flat blade and the third, four series of short paddles. With the single long flat blade agitator, the amount of powder moved by the blade was related to the torque. The relationship between torque and non-dimensional mean tangential velocity was demonstrated using phase diagrams. These remained unchanged with increase of agitator speed. The fluctuations of the torque with the long flat blade agitator were logically related to those for the single blade. The torque on the short-paddle agitator exhibited larger fluctuations which were strongly affected by the level of fill and the agitator speed. Powder cohesion had a significant influence on the mean and standard deviation of the instantaneous torque. Instantaneous torque measurement may be seen as a valuable method for process control.

Introduction

Developing fundamentals from laboratory experiments to industrial scale often represents a challenge in particle technology. This is particularly true in devices in which powders are mixed. However, there is now a range of activity in the literature as witnessed in recent papers. In 1995, McCarthy et al. developed a theory of powder behaviour in rotary drums. Metcalfe et al. (1998), provided some insights into powder flow in the cross-section of a rotating cylinder using MRI. Moakher et al. (2000), and Cleary et al. (2001), presented a comparative study between experimental results in tumbling blenders and results given by a discrete element model.

In the literature, it is argued that the mean torque \( \langle T \rangle \) and an angular velocity \( \omega \) can be correlated using a power number \( N_p = \frac{P}{\rho_{b} \omega^2 D^5 L} \) where \( P = \langle T \rangle \omega \) is the power, \( D \) the mixer diameter, \( L \) the mixer length, \( \rho_{b} \) the bulk density of the bed. \( N_p \) is a function of the Froude number \( Fr = \frac{\omega^2 D}{2g} \), where \( g \) is the acceleration due to gravity, and of dimensionless variables and parameters linked to powder properties. This has been employed by Müller and Rumpf (1967) amongst others. For a regime in which interparticle friction is dominant, they propose for a free-flowing powder that \( N_p \) is proportional to \( Fr^{-1} \). For a mixer of given diameter and length, this expression indicates that the torque is independent of speed and is proportional to bed density.

Positron Emission Particle Tracking (PEPT), a non-invasive method of investigation liquid or solid systems, provided much more information on powder flow patterns than other methods commonly used such as sampling. In PEPT, the motion of a single positron-emitting tracer is followed. The typical output is a data file containing the spatial co-ordinates of the tracer as a function of time. Particles moving at up to 20m/s have been followed. For the present work, the uncertainty of the positron camera in three dimensions or spatial resolution is approximately 2 mm for a speed of 0.2 m/s, and increases with the speed of the positron emitter to about 5 mm at a speed of 1 m/s (Parker et al., 1993). The tracer used here was a 0.6-mm-diameter resin particle containing absorbed water with \(^{18}\text{F} \) atoms produced by bombarding the water with \(^{3}\text{He} \) ions.

Studies using the PEPT technique include that of Broadbent et al. (1993) and of Jones and Bridgwater (1997), who investigated powder mixing in a plough-
share mixer. Experiments were also performed on fluidised beds (Parker et al., 1997). More recently, Laurent et al. (2000) provided for the first time the general description of the mixing patterns created by a single-blade agitator in a cylindrical shell. In the course of such studies on internal flow in mixers, information was also obtained on the torque. Here, this information is analysed and presented. It comprises instantaneous torque for a single-blade system, mean torque and torque fluctuations as the agitator moves through the particle bed. The study continues by examining how the blade structure determines the instantaneous torque, and offers proposals to assist the understanding of internal behaviour using information delivered by the authors in the previous work relying on PEPT.

Experimental Equipment and Materials

Experiments were conducted in a horizontal cylindrical mixer of diameter 270 mm and of length 650 mm. Three types of agitators were used. The first one, agitator A, is a simplified version of an industrial mixer, having six 53-mm-wide blades with an angular separation of 60°. The plane of each blade is inclined by 45° in radial direction. Each blade is supported at six points along its length by radial supports. Each of these supports has three radial plates with open space between and is fixed onto a 90-mm-diameter rotor shaft (fig. 1). Since two of the radial supports are close to the ends of the mixing chamber, the series of radial supports defines five axial compartments. The clearance between the tip of the blade and the inside of the cylindrical shell is 8 mm, and that between the blade tip and the inside of the end of the shell is 4 mm. The second device, agitator B, is a simplified version of the first agitator. Here, the radial supports carry one single flat blade as opposed to six. The third device, agitator C carries radial arms separated by 90° with mixing elements fastened to a rotor shaft of diameter 110 mm (fig. 2). The mixing elements are paddles of 97 mm by 46 mm inclined to form a 45° angle with the radial direction of the arms. Two sets of arms separated by 180° carry two series of five paddles each. The arms carry a further four rectangular bars, these being 104 mm long and of cross-section 19 mm by 19 mm. The clearance between the end wall and the paddles is 10 mm, that between the paddles and the cylindrical shell is 2 mm. A further two sets of arms, set at 90° to the others, carry four paddles and three rectangular bars.

The torque applied to the agitator shaft was measured by a torque gauge consisting of a set of strain gauges fixed on the surface of the rotating shaft and mounted to form a measuring bridge. The difference of potential created when a torque was applied was measured by a voltmeter to give a measure of the torque, the value being converted into a digital signal for acquisition by computer using an analogue-digital converter having a frequency of acquisition of 10 kHz. The linear range of measurement of the torque gauge was 0 to 200 Nm with a precision of 0.1%. The torque gauge was calibrated statically by a sequence of eight
weights fixed at the end of a horizontal bar fixed radially to the rotation axis. The digital signal produced by the converter corresponded to the known applied torque. This gave a linear relationship between the digital signal and the torque. Instantaneous torque was measured typically twenty times per second.

Two principal powders were used. Powder 1 had a bulk density of 510 kg/m³ with a mean particle diameter of 520 μm and an internal angle of friction of 30°. The powder was free flowing. Powder 2 had a bulk density of 420 kg/m³ with a mean particle diameter of 550 μm and was cohesive. The radioactive tracer had a diameter of 0.6 mm and true density close to that of the bulk particles, its motion thus representing the behaviour of the bed.

Analysis of results

The principal results employ powder 1; the effect of powder type is discussed at the end of this section.

Mean torque

Here, experiments conducted in the laboratory horizontal mixers are compared as a function of level of fill. The results are presented using the power number $N_p = \frac{P}{\rho_0 \omega^3 D^6} \frac{D}{L}$ in figure 3. This shows the influence of the agitator type on the power number for
F_r=0.22. The power consumption is higher for agitator C and the difference between the agitators A and C increases with the level of fill. Thus at a fill of 60%, the power consumption of agitator A is around a third that of agitator C. In order to seek an explanation for this difference, consider the area of the mixing elements (including the blades, the rectangular bars and their supports) projected onto a plane passing through the axis of rotation. The projected surface of the mixing elements is 960 cm² for agitator C and 1520 cm² for agitator A. One thus sees that the projected surface of the mixing elements is not the dominant factor; this matter is pursued below.

If the level of fill is below 40%, then the mean torque needed for the single blade (agitator B) is less than the six-blade agitator A, whereas the converse is found if the level of fill exceeds 40%. This is ascribed to the existence of slip surfaces within the material for the single-blade system whereas for the six-blade agitator, the powder moves as a block around the inner surface of the mixer shell.

Figure 4 compares the mean torque as a function of \( \ell \) for the six-blade agitator A with the single-blade agitator B, where \( \ell \) is the length of the circumference of the mixer in contact with the particle bed. The level of fill corresponding to \( \ell \) is also represented on a double axis. The circumferential length is thought to be a significant parameter since the application of a torque on the shaft results in frictional forces on the mixer bowl which might be expected to be proportional to the surface area in contact with the powder bed.

At 20% of fill, the mean torque for agitator A is roughly twice that for agitator B, this suggesting that two blades of agitator A are in the bed at the same time. At 40% of fill, the mean torque is the same for agitators A and B. At 60% of fill, the mean torque for agitator B is around twice that for agitator A. Hence, increasing the number of blades does not increase the torque in a proportional manner. For the single-blade agitator B it may be suggested instead that the bed reconsolidates between each blade pass. This means that the single blade of agitator B has to overcome the stress necessary to put the material in a state of incipient failure, whereas the bed is continuously stirred by the six-blade agitator A. This implies that the local bulk density of the bed is lower with agitator A and that stresses in front of each blade will be less with more blades stirring the bed, leading to a lower torque due to each blade.

**Flow structure and instantaneous torque**

**Agitator B**

Figure 5 shows the influence of the level of fill on the torque reported as a function of blade position. The results plotted have been adjusted by subtracting
the torque measured with no fill in order to take into
account the lever effect exerted by the single blade;
the associated fluctuation has an amplitude of 1 Nm.
The blade angle co-ordinate is defined to be zero
when the leading edge of the blade is directly below
the centre of the shaft. The position of the powder
bed in the mixer is obtained using PEPT (fig. 6).

Consider first the torque corresponding to a level of
fill of 20%. The signal is low when the blade is out of
the particle bed, i.e. blade position of $120^\circ$ to $315^\circ$. As
the blade penetrates into the bed, the torque in­
creases and reaches its maximum when the blade
position is $30^\circ$. It then decreases as the blade moves
towards the free surface and then out of the bed.

Figure 6 shows the occupancy, i.e. probability of
finding the tracer particle, integrated along the whole
length of the mixer, and gives a measure of the local
bulk density. Thus figure 6 b) corresponds to a
blade position of around $30^\circ$ for 20% of fill. The bed is
being pushed along the wall and is also being slightly
raised. Material does not flow over the shaft, and cas­
cading over the blade is about to start. The maximum
value of the torque increases with level of fill; the
blade position at which the torque is a maximum
changes its phase, this changing from $25^\circ$ at 20% of
fill to $330^\circ$ at 60% of fill.

Figure 7 shows the occupancy for a level of fill of
60%. The dotted line marks the approximate position
of the free surface of the bed. Thus figure 7 b) corre­
sponds to the approximate blade position where the
torque is maximum for 60% of fill, and shows the
blade being engaged into the whole bed and sliding it
along the wall. Most of the material is pushed over
the shaft.

At all levels of fill, the torque decreases and reaches
a value which is not zero when the blade is out of the
bed. This is due to the action of the friction forces
on the radial supports of the blades described in
figure 1. As the level of fill increases, this value
increases since the contact area between the particle
bed and the radial supports increases. Figure 4 also
presents the mean of the torque for both agitators A
and B from which the base of the signal for agitator B,
as just defined, has been subtracted. This procedure
is correct for agitator B but an approximation for agi­
tator A, as the particle bed does not relax to rest and
may even be fluidised. The resulting signal is inde­
pendent of fill for agitator A and follows the same
trend for agitator B. This demonstrates that the
single-blade agitator B has to overcome a reconsolida­
tion effect after each blade pass, whereas the bed is
constantly stirred by agitator A, leading to a torque
that is independent of the amount of material in the
mixer.

Fig. 6 Cross-sectional view of agitator B for six different blade
positions, 20% of fill, 38 rpm

Fig. 7 Cross-sectional view of agitator B for six different blade
positions, 60% of fill, 38 rpm
In both cases (i.e. with/without the base signal), the curves for the two agitator types intersect for a fill of around 40%, which is thought to be a critical value as the flow patterns switch from pure cascade mode to channelled flow between the agitator shaft and the cylinder wall. For the six-blade system, the blades in the bed have an associated but strongly non-additive effect. The signal corresponding to the base of the single-blade agitator B is mainly believed to be due to the friction forces of the radial supports. The signal for agitator A, from which the base value has been subtracted, shows that the value of the torque is practically independent of the amount of fill in the system. It follows that the material rotates as a core around the central shaft. This means that the number of blades does not then have any influence on the torque necessary to rotate the core of material. It is to be expected that there is a critical value of angular spacing of blades below which the system returns to rest between each blade pass.

Analysis of PEPT data provides direct access to the mean tangential velocity of the tracer, offering this parameter as a way of characterising the powder flow. Figure 8 presents the mean tangential velocity and the torque measured on the agitator shaft versus the blade position for three levels of fill 20%, 40% and 60%. Between 180° and 270°, the blade is always out of the particle bed, the tangential velocity is low since the bed is in or close to a rest state at all levels of fill. As the blade moves into the bulk and reaches 315° for 20% of fill, 300° for 40% of fill and 250° for 60% of fill, the tangential velocity increases progressively. The tangential velocity then increases progressively to reach a maximum for a blade position of 0°, 345° and 330° at a fill level of 20%, 40% and 60%, respectively. At a blade position of 90° for 20% fill, the velocity decreases to reach a minimum. As the blade moves further out of the particle bed, the tangential velocity increases and reaches a value close to zero when the bed returns to the rest state.

Compare now the torque with the tangential velocity for one blade rotation. Between 180° and 270°, the tangential velocity is very low and the bed is at rest. Over this angular interval, the torque is low as the blade is out of the particle bed at all levels of fill. The signal is then due to the frictional forces between the bed and the radial supports (fig. 1), to the friction at the bearings supporting the rotating shaft together with the torque due to asymmetry of the radial arms and blade. The torque starts to increase for a blade position of 315° for 20% of fill, 270° for 40% of fill and 250° for 60% of fill; this corresponds to the blade entering the particle bed. This is in agreement with the approximate position of the lower point of the free surface (figs. 6, 7).

At 20% fill, the torque increases further as the blade moves through the bulk and reaches a maximum when the blade position is 30°. This can be related to figure 6 c) showing how part of the bed is lifted by the blade. The maximum in the torque occurs when all the material is being lifted by the blade before it cascades into the void behind the blade. As material cascades down the free surface of the bed, less material is lifted by the blade and the torque decreases; the tangential velocity becomes negative since, at this level of fill, material is flowing down the free surface in anti-clockwise direction below the centre of the agitator. As the blade moves out of the bulk, the mean tangential velocity reaches a minimum. Most of the motion in the bed then occurs at the free surface. Once the blade is completely out of the particle bed, the torque is low and the mean tangential velocity increases to reach a value close to zero. This phase brings the bed back to its initial state.

As the fill increases, most of the material moves over the agitator shaft in clockwise direction; the tangential velocity stays positive as a result. The torque can be again related directly to the flow structure developed.

Phase diagrams offer a way of relating the torque to the tangential velocity. The parametric curve quantifies the phase between the two signals. Figure 9 shows the influence of the fill on the phase diagram of the torque vs. mean tangential velocity, the agitator speed being 38 rpm. At 20% of fill, the parametric curve of torque vs. tangential velocity is a flattened ellipse, the direction of rotation being anticlockwise, implying that the tangential velocity is ahead of

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Fig. 8 Mean tangential velocity of the tracer and torque vs. blade position, agitator B, 36 rpm
torque. The diagram indicates the position of the blade in the bed. Both the tangential velocity and the torque reach their minimum in the range of blade positions 180° to 270° as the bed is then at rest. The shape of the curve remains the same up to 40% of fill, although the ellipse is here less flattened, i.e. the phase between the tangential velocity and torque has increased. At 50% of fill, the shape of the curve has dramatically changed and becomes octagonal. This level of fill is considered to represent a change in the patterns inside the cylinder, being at the transition point below which the powder cascades essentially onto the free surface below the agitator shaft and above which the powder rotates mainly around the agitator shaft. At 70% fill, the shape of the curve has reverted to an ellipse which rotates here in clockwise direction, showing that tangential velocity is now lagging behind torque.

Using the same presentation, figure 10 shows the influence of the agitator speed on the phase diagram of the scale torque vs. the non-dimensional tangential velocity, the level of fill being 60%. Here, the amplitude of the curve is not affected by the agitator speed. This feature is related to the general non-dimensional structure of the flow being kept invariant with respect to the agitator speed, i.e. flow displacements scale with the number of blade passes. However, close observation of the shape of the curves shows that the shape is not kept invariant with increase of speed. At 20 rpm and 25 rpm, the curve is slightly elliptic, rotating in clockwise direction, showing that the tangential velocity is lagging slightly behind the torque. At 38 rpm and 45 rpm, the curve becomes octagonal.

**Agitator A**

Figure 11 illustrates the torque for agitator A; data for the single-blade agitator B are included for comparison purposes, the level of fill being 60% and the rotation speed 38 rpm. The signal for agitator A exhibits six peaks, each of these being spaced by 60°. These peaks correspond to the six flat blades of the agitator. The amplitude of the fluctuations of the torque for agitator A is here around 3% of its average of 8 Nm. The torque measured with the single-blade agitator reaches a maximum for a blade position of 330°, for which a peak in the torque for the six-blade agitator A also appears.

The time-occupancy diagram for agitator A is pre-
Fig. 10 Influence of speed on the phase diagram (torque vs. tangential velocity), agitator B, 60%
Parameters on curves: blade position in the bed; 0° origin: blade in lower vertical position

Fig. 11 Torque vs. blade position; agitators A and B, 38 rpm; level of fill: 60%

represented in figure 12 a) and shows the existence of two zones of higher probability of presence of the tracer. The first zone is situated beneath the rotating shaft, immediately above the dotted line showing the locus of the inner radius of the rotating blades. The second region of higher occupancy lies in the clearance between the locus of the tip of the blade and the inside of the shell. By comparison, figure 12 b) shows the time-occupancy diagram for the single-blade agitator B. This diagram is integrated over all the blade positions. It exhibits similar regions of higher density as for the six-blade agitator A, although these regions appear less clearly. The region of higher density situated beneath the agitator shaft corresponds to a loop of circulation where agitation is poorer, as reported in an earlier work by Laurent et al. (2000).

Agitator C
For the short-paddle agitator C, the torque observed is periodic at all levels of fill investigated. Figure 13 a) gives an example of the signal as the fill varies from 20% to 70%. The periodicity of signals being π, we show only half of the full cycle. For a level of fill of 60%, the amplitude of the fluctuations of the torque is in this case 50% of its average compared to 3% for the six-blade agitator A for the same fill. The peaks of the torque correspond to the paddles and rectangular bars fixed on the four series of arms sepa-
rated by 90° each. The angular position of each peak corresponds to a radial arm forming an angle with the vertical of 60°.

Consider the torque for 20% of fill. The blade position of 0° corresponds to the lower vertical position of one of the series of arms carrying four paddles. The signal increases and reaches its maximum for a blade position of 30°, which corresponds to four paddles being in the particle bed. Then the torque decreases as the blades move out of the bed. It increases again, here due to the five paddles penetrating into the material, and peaks for a blade position of 120°. The cycle then resumes with the other set of four and five paddles. The signal shows that the peak corresponding to the five paddles being in the middle of the bed is slightly higher than the other peak corresponding to the four paddles.

With increase of fill, the difference of amplitude between the two peaks increases. The position of the peaks is altered, the maximum of the torque corresponding to the five paddles being 120° at 20% of fill and 60° at 70% of fill. At this fill, the peak corresponding to the four paddles has been absorbed into the other peak.

Figure 14 a) shows the influence of the agitator speed on the angular distribution of the torque for powder 1. The mean torque is not affected by an increase of speed. However, the shape of the signal changes dramatically. At low speed, the signal exhibits two peaks, corresponding to the two different series of arms carried by agitator C. The ratio of the two peaks is around 0.86. By comparison, the ratio of the projected surface of the mixing elements (paddles and rectangular bars) of the arms carrying five paddles to those carrying four paddles is about 0.81. As the agitator speed increases, the ratio of the two peaks decreases and reaches 0.65 for a rotation speed of 60 rpm. By then, the lower peak has been practically absorbed into the other dominant peak. The maximum has also been shifted towards a higher blade position in the bed, corresponding to a delay in phase.

Figures 12 a), b) and c) show comparative performances for agitators A, B and C at 50% of fill. Two
zones of higher density appear with agitator C, one beneath the shaft and the other immediately above it. As the agitator rotates, material is able to escape to the rear of a paddle of this agitator through the space between adjacent blades. The boundaries are not as distinct as those of the higher density zones for agitator A because the mixing elements of agitator C leave less material in the mixer cross-section unaffected by the blades and the rectangular bars. This is a likely explanation of the higher power consumption with the short-paddle agitator C. Thus the rectangular bars of agitator C operate between radial positions of 70
and 90 mm, and the paddles between ones of 100 mm and 133 mm. These rectangular bars eliminate the zone of little radial agitation observed with agitator A. These observations suggest that material has more even radial distribution in the cross-sectional plane with agitator C, as confirmed in figure 13 a) and c).

Influence of the powder

The experiments reported in figures 13 a) and 14 a) for powder 1, the free-flowing powder material, were repeated for powder 2, the cohesive material. The findings are given in figure 13 b) and 14 b). From figure 13, we see that the mean torque at 20% fill is greater for powder 2 and the amplitude of the fluctuations is reduced. On increasing the fill, the second peak corresponding to the four paddles is lost even at 30% fill. Allowing for the difference in bulk densities by supposing that torque is proportional to the bulk density enhances the differences. With powder 2, a cohesive material, we deduce that the correlation established by Müller and Rumpf (1966) is incomplete. Figure 14 b) shows the effect of speed; the behaviour of the two systems is again markedly different. The mean torque could be used as a characterisation of the material in the mixer. However, the standard deviation is also a sensitive parameter.

Figure 15 presents the standard deviation of the torque vs. fill for both powders 1 and 2. It shows a remarkable linear relationship, particularly for the cohesive powder 2. It also shows that the amplitude of the oscillations is lower for the cohesive powder 2 than for the free-flowing powder 1. This demonstrates the potential for on-line instantaneous torque measurement to control an industrial process. Indeed, these diagrams can be used to relate the mean torque and torque fluctuations to the operating parameters of the system as well as the quality of the product.

When PEPT experiments are performed with powder 2 (fig. 12 d) and e), we find with agitator A that the material is more concentrated between the inner shaft and the inner tip of the blades; the region of bed less influenced by the blade is emphasised. For agitator C, a body of material is found above the shaft with a more open region in the horizontal plane of the inner shaft.

Conclusions

Experiments have been carried out here with three horizontal cylindrical mixers. The systems have been discussed using the mean torque, instantaneous torque, particle tangential velocity and powder occupancy of each mixer. Three designs have been employed.

Investigations using a single-blade agitator showed that as the blade progresses into the particle bed, the increase of torque corresponds to an increase in the mean tangential velocity. The torque is a maximum for a blade position corresponding closely to the maximum of the mean tangential velocity. In this system, the powder is moved in a series of pulses by the blade and comes back to rest after each blade pass.

The torque measured with a six-blade agitator was found to be periodic, having a frequency six times that of the agitator speed. Each peak of the torque corresponded to the same blade position as for the single-blade agitator. However, the mean could be less than the mean torque for just a single blade because the whole of the material is kept in constant motion by the multi-blade agitator. The torque was found to be 30% lower at 20% of fill with the six-blade agitator than with the short-paddle agitator. This difference increased with the level of fill.

The instantaneous torque and the mean tangential velocity can be conveniently related using phase diagrams. It can happen that the mean tangential velocity leads the torque, as well as the converse. The variations of speed, level of fill and cohesion of the material are all manifest in the relationship between instantaneous torque and blade position.

For the future, instantaneous torque can thus be used as a simple and effective means of monitoring and controlling process operation. The knowledge of the mean and fluctuations of torque at drive and
vessel support, or even internally on the mixing elements, would be of further theoretical and industrial interest. Analysis of instantaneous torque provides a means of gaining insight into the scale-up of vessel diameter, a significant and unresolved issue.

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**Notation**

| Symbol | Unit   | Description                        |
|--------|--------|------------------------------------|
| D      | [m]    | Mixer diameter                     |
| L      | [m]    | Mixer length                       |
| \( \mathcal{L} \) | [m]   | Circumferential length             |
| N      | [rpm]  | Agitator speed                     |
| P      | [W]    | Power                              |
| <T>   | [Nm]   | Mean torque                        |
| \( \rho_b \) | [kg/m^3] | Powder bulk density               |
| \( \omega \) | [rad/s] | Agitator angular velocity         |

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