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

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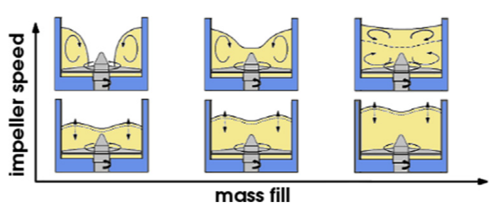
HIGHLIGHTS

- An improved model for torque analysis in high shear mixers of cohesive powders is proposed.
- Surface velocity and torque mesurements where found to be uncorrelated at high fll level and impeller speed.
- On the surface of the powder bed convective cells with low surface renewal were observed at high fill level.
- In addition to the roping and bumping regimes a new regime with low mixing efficiency is described in full-scale mixers.

GRAPHICAL ABSTRACT



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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.

1. Introduction

High shear mixers, also known as high intensity mixers (Manjunath et al., 2003), are widely used for the powder

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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 and Ennis, 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 behavior 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 et al., 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 a 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. Manjunath 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 and Chen, 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 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 (Muzzio et al., 2003; Landin et al., 1996a,1996b) 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 (Fig. 1) and the pilot-scale mixer (Aeromatic Fielder PMA 65L, Eastleigh, Hampshire, UK) was bottom driven (Fig. 2). Both of the mixers had stainless steel vessels and three bladed impellers. Impeller blade angle was about 30° for both of them.

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%

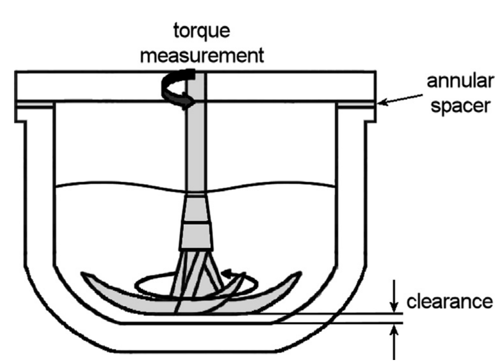

Fig. 1. Schematic of the bench-scale mixer. Impeller is three bladed, top-driven and equipped with a torque measurement and registration system.