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A numerical comparison of mixing efficiencies of solids in a cylindrical vessel subject to a range of motions

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ABSTRACT

The mixing of solids is a fundamentally important unit operation in the pharmaceutical, food and agricultural industries, as well as many others. The efficiency and quality of mixing can have a significant bearing on downstream processability and product quality. In spite of the fact that the equipment, usually batch blenders without impellers such as tumbling bins and V-Blenders or with impellers such as ploughshare mixers, is well established, there remains considerable uncertainty in the optimisation of mixing. Simple laboratory/pilot scale mixers based on the rotating drum, such as the hoop mixer and the Turbula, are commonly used and yet also little understood in terms of performance. These mixers add additional rotational and/or translational movements to the cylindrical rotation of the drum to deliver significant improvements in mixing, particularly in the longitudinal axis.

Discrete Element Modelling (DEM), in which a flowing or deforming granular system is modelled by considering the movement of each individual particle and its interaction (momentum and energy exchange) with neighbours and boundaries, has recently become accessible to relatively non-expert users. The reasons for this include: increasing confidence in its capability; user-friendly graphical interfaces of commercial software packages; and the fact that top end personal computers now have sufficient memory and computational speed to enable many problems to be solved in weeks rather than months.

The purpose of the work reported here is to evaluate the power of DEM to help understand flow processes and explain mixing mechanisms in mixing equipment based on the rotating drum. The commercial package EDEM (from DEM Solutions) was used. For speed and simplicity the modelled system comprised monosized smooth glass beads. Three mixers were selected: horizontal rotating drum, the hoop mixer and the Turbula. The rate and extent of mixing, quantified using a "segregation index" based on contacts between two discretely labelled but otherwise identical fractions, was shown to depend on equipment motion, operating speed and the initial distribution of the fractions. The well known characteristics of the horizontal drum operating in rolling mode were demonstrated: excellent transverse mixing and poor axial mixing; both improving with speed as the depth of the active layer is shown to increase. The hoop mixer incorporates off-axis rotation, causing periodic tilting of the cylinder axis. This results in a considerable improvement in axial mixing. Interestingly, at low speeds the hoop mixer and simple rotating drum exhibit similar transverse mixing but increasing speed has the opposite effect: improving transverse mixing in the drum while worsening it in the hoop. Axial mixing in the hoop mixer, on the other hand improves with speed. The Turbula displays a very interesting relationship with speed. At low speeds, its transverse mixing performance is the same as the horizontal drum and hoop mixer but decreases significantly with increasing speed, going through a minimum at medium speed before recovering completely at high speed. Axial mixing is comparable, showing the same trend. It appears that the motion in the Turbula goes through some sort of transition that has a profound effect on mixing performance. The implication is that unless this is understood, it will be difficult *a priori* to identify optimum operating conditions.

The power of DEM lies in the fact that the complete trajectory of each particle is recorded: it is possible to follow the movement, deformation and breakup of clusters of particles. From this it should be possible to elucidate the dominant flow mechanisms and to identify those that have the most impact on mixing. This presents a challenge to develop methodologies for cluster analysis and visualisation and is the subject of on-going work. Other work is focussed on experimental validation of the DEM predictions.

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1. Introduction

Granular media are of great importance in many manufacturing processes across different disciplines, for example in pharmaceutical, chemical, food, ceramics, plastics, fertilisers, detergents, glass, and powder metallurgy industries. Powder mixing is one of the most widely used operations in industry. Often, particulate materials are mixed for subsequent operations such as compaction where particles are mixed with lubricant materials, such as graphite, to improve material flow during die filling and to decrease friction and adhesion between the die wall and tablet surface during ejection. The mixing of particulate material is therefore an important stage in reaching the desired final product quality or the right manufacturing conditions, however it can often be difficult to mix particles homogeneously. Controlling the mixing mechanisms is key in achieving the desired characteristics for a final product; this is difficult to design from first principles since, in spite of considerable research, fundamental understanding remains incomplete. The mixing mechanisms will depend on the mixing action of the mixer (a wide range of possible designs) and the flow behaviour of the particles. Granular mixing operations are usually batch-wise, however in certain cases, can be a continuous process, and even the same equipment can be used in batch or continuous mode. A variety of solid mixers are available in industry. They can be divided mainly in two categories, mixers with rotating vessels and mixers with fixed vessels. Mixers can also be grouped depending on the predominant mixing mechanisms such as convection, dispersion or shearing. Rotating cylinders for example are widely used as mixers. In batch mode they usually they consist of a horizontal cylinder rotating around the central axis [1–5]. The motion of the granular bed is predominantly rotation about the cylinder axis with a cascading free surface: mixing occurs predominantly in the cross-section with some axial dispersion [6]. Recent studies have shown that the slow axial mixing, can be enhanced by incorporating a rocking motion of controlled amplitude and frequency [7], this added perturbation accelerates the mixing process. Other types of motion can therefore be applied to try to enhance mixing in the axial direction: the hoop mixer and Turbula mixer are typical examples. In both of these examples the material to be mixed is placed inside a cylindrical mixing vessel which is then subjected to complex, yet regular, motions.

In the hoop mixer the longitudinal axis of the cylindrical container is inclined at an angle to a horizontal axis of rotation. Under this condition the granular bed is subjected to radial and axial movement as a result of the gravitational forces which are acting periodically in the axial direction due to the inclination and the revolving movement of the cylinder [8].

The movement of the cylindrical container located within the Turbula mixer chamber comprises two rotations and a horizontal translation. The material within the vessel is therefore subjected to intensive, periodically pulsating movements as result of the sharp reversal in direction of translation and the rapid change in orientation of the vessel [9–11]. It has been shown that the Turbula mixer can achieve rapid uniform mixing even for systems that would segregate in a simple rotating drum [12].

2. DEM numerical model

Discrete Element Modelling (DEM) is a numerical tool that models a granular system as an assembly of discrete particles, which interact with each other and with any other solid body such as vessel walls and mixing impellers. Cundall and Strack first proposed the discrete element method for modelling the motion of granular material [13]. This numerical technique has been extensively used to simulate rotating mixers [14–19].

A commercial three-dimensional DEM code (EDEM® 2.3, DEM Solutions) has been used in this work. For every individual particle, the position, the velocity, the acceleration is calculated according to Newton's equations of motion Eqs. (1) and (2).

$$m_i \frac{dv_i}{dt} = \sum_j^n \left(\mathbf{F}_{ij}^n + \mathbf{F}_{ij}^t \right) + m_i \mathbf{g} \quad (1)$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_j^n \left(\mathbf{R}_i \times \mathbf{F}_{ij}^t - \boldsymbol{\tau}_{ij}^r \right) \quad (2)$$

where $\mathbf{R}_i$, m_i, $\mathbf{v}_i$, $\boldsymbol{\omega}_i$ are the radius, mass, translational and rotational speed of the ith particle. F_{ij}^n and F_{ij}^t are the normal and the tangential force in inter-particle or particle–wall collisions according to the Hertz Mindlin contact model implemented into EDEM [20]. The term τ_{ij}^r is added to account for the torque caused by rolling friction resistance.

2.1. Geometry and simulations conditions

Three different motions have been applied to a cylindrical container, 45 mm in diameter and 80 mm in length, as shown in Fig. 1. In case (a) the cylinder is horizontal and rotation is applied around the horizontal cylindrical axes (rotating drum). In case (b), the hoop mixer, the cylinder axis is offset from a horizontal axis of rotation by a 30° inclination angle. In case (c) the cylinder is driven by a motion corresponding to the motion of a cylinder located inside the chamber of a Turbula mixer [10,11].

In these studies, the granular system comprises two differently coloured and initially segregated fractions of otherwise identical monosized spherical particles. Mixing is measured from the intermingling of the two fractions. In order to separately study mixing in the vessel cross section (transverse and radial) and mixing along the vessel length (axial), two different initial filling conditions have been considered,

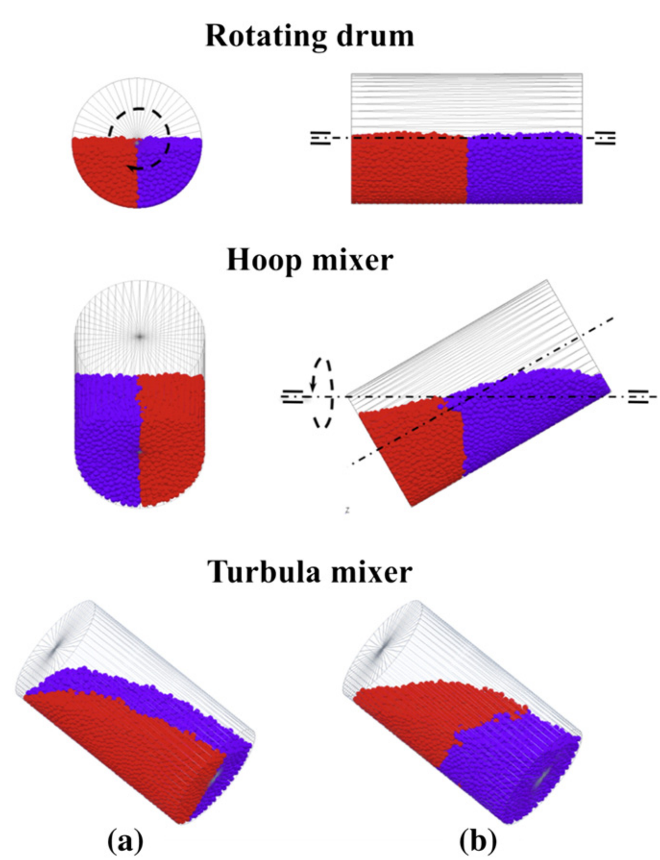

Fig. 1. Representation patterns used in the simulation for the three mixers. (a) Transverse filling. (b) Axial filling.