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Dem investigation of horizontal high shear mixer flow behaviour and implications for scale-up

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ABSTRACT

In high shear granulation, various dimensionless or dimensioned parameter groups such as constant Froude number, tip speed, relative swept volume and specific energy input are commonly used as scale-up criteria, in order to maintain the powder bed internal flow or stress field across scales. One major challenge is obtaining the internal flow and stress field through experimentation given the lack of precise measurement techniques. Hence, this work employs DEM (**d**iscrete **e**lement **m**ethod) simulations to study the internal flow patterns and behaviour of different scale batch, horizontal high shear mixers. The simulations provide a deeper understanding of the interaction of scale, impeller speed and fill level on the flow field, and show that the particle velocity is correlated with the relative swept volume in these mixers. It shows that the relative particle velocity is correlated, independent of scale, to the relative swept volume per rotation and highlights its values as a parameter for understanding and comparing mixer behaviour. The work also demonstrates the importance of the particle size chosen for the simulation as well as the tool-wall gap in the mixer, and highlights its importance as we interpret DEM results.

1. Introduction

Wet granulation or agglomeration is a particle enlargement process used widely in detergent, pharmaceutical, food and agriculture industries, where powders are held together by inter-particle bonds with the addition of liquid binder to produce granules with enhanced properties. Amongst the wet granulation techniques, high shear mixer granulators contain mechanical blades and choppers that exert impact and shearing forces on the granulating mixture to promote binder distribution, mixing, coalescence, granule consolidation as well as breakage. There are several high shear mixer configurations, categorised as horizontal or vertical shaft mixers and the latter can be either top- or bottom-driven [1].

In high shear granulation, maintaining the targeted product attributes upon scale-up to larger granulator usually used for production, is an important yet challenging area of study. As reviewed by several researchers [2–4], granulation scale up is typically carried out based on macroscopic approach, i.e. by controlling equipment parameters, such as operating conditions and equipment geometries. This is done by fixing one or a few dimensioned or dimensionless parameter groups as the scale up criteria. These parameters include tip speed, Froude number, relative swept volume, specific energy input, power number, Reynolds number and spray flux [2–4]. In general, the following similarity across mixer scales should be maintained to control agglomeration conditions (besides liquid delivery conditions): geometric, kinematic (i.e. internal particle flow) and dynamic similarities (forces or energy on particles) [5]. As it is not straightforward to obtain the internal flow and stresses through experimentation, kinematic and dynamic similarities are often not discussed and established in scale-up work. Most experimental flow studies in high shear mixers are focussed on the surface flow using high speed imaging [6–10], while some studies on the internal flow were carried out mostly using the Positron Emission Particle Tracking (PEPT) technique [11–14], although this technique is costly, less accessible and limited to velocities below 2 m/s [15,16]. Advances in computer simulations, however, have enabled the internal flow, stresses, torque and mixing efficiencies to be studied via **d**iscrete **e**lement **m**ethod (DEM), see examples: [10,11,13,17–23] or **c**omputational **f**luid **d**ynamics (CFD), see examples: [24,25].

For scale up studies, little work has focussed on studying the internal flow [12,13,23] and stresses/energies [23,26,27] in different scales vertical axis mixers. Ng et al. [12] and Hassanpour et al. [13] measured the internal flow using the PEPT method, while Nakamura et al. [23] investigated the internal flow using DEM. Both Ng et al. and Nakamura et al. found that the internal flow/kinematic similarity is maintained using constant tip speeds, i.e. a scaling exponent, n, of 1 for the impeller speed-mixer diameter scaling relationship (Eq. (1)), where ω and D

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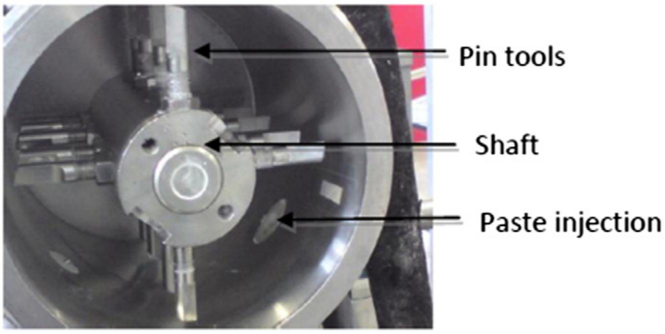

Fig. 1. Custom-made, batch Lodige mixer.

Table 1
Mixer and pin geometry.

Mixer relative volume, V^* [–][a]	Mixer relative internal diameter, D^* [–][b]	No. of pins [–]	Gap/mixer radius, G/R [–]
1	1	16	0.034, 0.074
15	2.9	16	0.034, 0.074
54	4.7	16	0.034, 0.074

[a] $V^* = V/V_{base}$
[b] $D^* = D/D_{base}$

Table 2
DEM input parameters.

Particle density (kg/m^3)	1250
Particle Young's modulus (MPa)	10
Particle Poisson's ratio (–)	0.25
Wall Young's modulus (MPa)	10
Wall Poisson's ratio (–)	0.3
Particle–particle restitution coefficient (–)	0.4
Particle–wall restitution coefficient (–)	0.4
Particle–particle sliding friction coefficient (–)	0.5
Particle–wall sliding friction coefficient (–)	0.5
Particle–particle rolling friction coefficient (–)	0.1
Particle–wall rolling friction coefficient (–)	0.1
Simulation time step (s)	1×10^{-5}

are the impeller speed and mixer diameter respectively. On the other hand, Tardos et al. measured the granule shear stresses indirectly by adding "test" particles with known yield strength into the granulating mixture and measuring the breakage fractions [26], while Fu et al. inserted a probe affixed with pressure colouring films into the granule bed to measure the impact stress [27]. For constant shear stress, Tardos obtained scaling exponent, n of 0.8–0.85. Fu also obtained a value close to that for constant impact stress, i.e. $n = 0.755$.

$$\frac{\omega_2}{\omega_1} = \left(\frac{D_1}{D_2}\right)^n \tag{1}$$

In addition to maintaining the kinematic similarity, Nakamura et al. proposed a combined kinematic–dynamic scale up method [23]. For dynamic similarity, they proposed a constant particle collisional energy approach. They found that the averaged cumulative collisional energies, analysed with DEM, reduce with scale due to less particle circulation. With this, the process time was scaled to maintain the collisional energy. They also validated the proposed scalings experimentally.

This work is focussed on studying the internal flow of different scale batch horizontal high shear mixers using DEM, followed by kinematic similarity scaling. These are the custom-made, batch versions of continuous Lodige mixers used for manufacturing. From the literature above, most high shear mixer flow studies were for vertical shaft mixers, and this work will provide some insights on the flow in the horizontal Lodige type mixers. For simplicity, mono-sized and cohesionless particles are simulated. Fig. 1 shows the mixer which contains pin tools acting as the mixing, cutting and shearing elements. Three mixer scales (Fig. 2) were simulated in this work to study the impact of scale. Table 1 shows some relative dimensions of the mixers and exact geometrical details are not disclosed due to confidentially. The mixers' internal diameters and volume are normalised against the smallest scale mixer (left-most in Fig. 2) dimensions respectively. Note that the mixers also have a different length to diameter ratio while the width of the pins scales with the mixer length. The mixers contain the same number of pins. Due to the intense operation of these mixers, a sufficient gap has to be maintained between the pin tools and the mixer wall for safety purposes. Therefore, two different sets of pin-wall gap ratios were studied, by keeping the gap to mixer radius, G/R, constant across scales (Table 1).

2. Simulation method and setup

In this paper, the soft sphere DEM model for deformable particles which was originally proposed by Cundall and Strack [28], was applied to simulate the particle motion and interaction forces. The translational and rotational motions of particles are simply given by Newton's law of

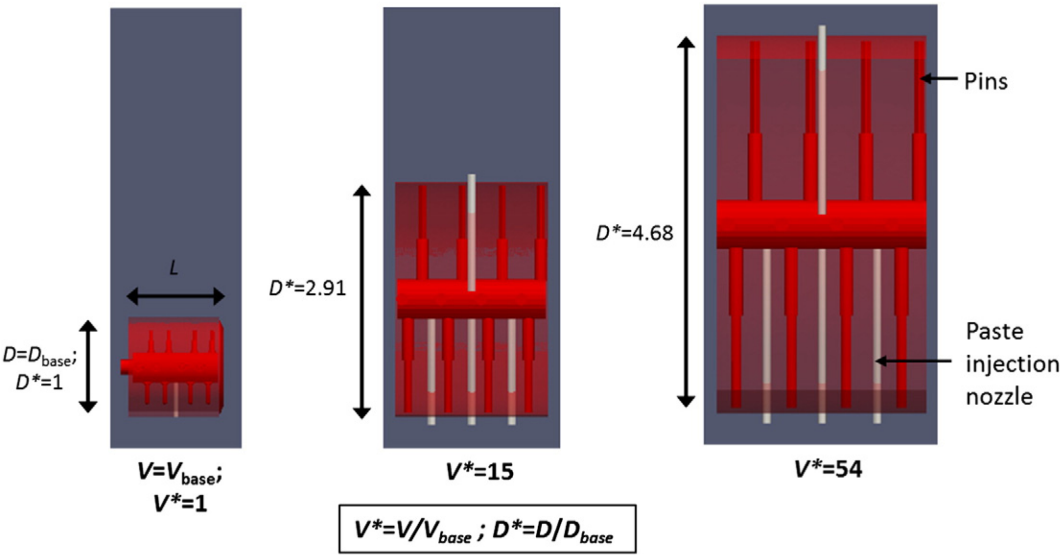

Fig. 2. Mixer scales (from left): $V^* = 1$, $V^* = 15$ and $V^* = 54$.