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Characterization of granular mixing in a helical ribbon blade blender

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ABSTRACT

Experiments of bulk solid mixing in a twin ribbon blade blender have been performed in this work in order to characterize mixing behavior in such a mixer for binary mixtures with different cohesionless materials. The effects of fill height and blade rotation speed on mixing homogeneity have been studied. Mixing homogeneity was determined by sampling. It has been observed that mixing is relatively fast towards a final mixing state within approximately 100 blade rotations for different combinations of material, fill height and blade rotational speed. Moreover, these final mixing states seemed stable within a range of fluctuations, which may prove useful in determining an optimal mixing time for binary, cohesionless particle mixtures and potentially lead to a reduction in the required number of blade rotations in mixers of this type in industry. Mixing homogeneity results indicated an increased final mixing homogeneity for increasing fill height, most clearly in the range of 30–70 vol.% in the studied twin ribbon blade mixer. The torque on one of the shafts was determined. The latter results showed that no significant influence of rotational speed on the required torque for the tested mixtures at rotational velocities in the range of *Fr* 0.17–1.1 could be determined for most combinations of the tested materials and fill heights in this work. The quantitative characterization of mixing behavior with the two key parameters mixing homogeneity and torque on the shaft may be used for mixer validation of DEM simulations.

1. Introduction

Granular mixing is a unit operation encountered in many process industries and has been a topic of experimental research for many decades [1–8]. It plays an important role in e.g. preparing correct amounts of active pharmaceutical ingredients for tablets or ensuring constant product quality in detergents or blends of spices. In contrast with the mixing of fluids, mixing of particles is difficult to predict due to e.g. distribution of properties such as particle size and shape leading to phenomena such as segregation. This is why the study of granular mixing and determining the 'mixedness' of a granular mixture often remains mainly empirical and mixing behavior is still hard to predict reliably.

Determining the 'mixedness' or mixing homogeneity empirically was mostly done in the experiments by sampling. Reviews on sampling and sampling theory have been published in [1,4,7–11]. However, sampling is laborious and may be prone to errors, since this method is intrusive and may therefore disturb the mixing state. With the advent of simulation using the Discrete Element Method (DEM), originally proposed by Cundall and Strack [12], as a new means of studying granular mixing challenges, the topic greatly attracts the interest from academia and industry. DEM simulation offers the opportunity to study granular mixing in a non-intrusive way and to save part of these experiments. However, the results from these DEM simulations require experimental results for validation. While studying batch mixers, velocity profiles near walls and particle trajectories were often chosen as parameters to validate or compare simulation results with laboratory experimental results by e.g. particle image velocimetry (PIV) [13,14] and positron emission particle tracking (PEPT) [15–19] techniques respectively. PIV can provide particle velocity profiles using high-speed camera images of the particles in a defined section of the system near a wall. Local mixing homogeneities near the wall may be determined from particle positions on these images as well. PEPT offers the opportunity to track one or more particles throughout the mixer and in this way establish particle velocity profiles. These methods are very powerful as they offer the advantages of being non-intrusive and of providing particle velocity results that can be directly compared with simulation results [16,18]. However, PIV is limited or incapable of providing direct information on the mixing homogeneity of the inner parts of a mixer, which becomes more important in larger systems as encountered in industrial practice. PEPT is capable of studying the inner parts of an opaque system in a mixer by tracking one or a couple of particles, providing information of one or some positions in the mixer at a time. It was demonstrated by Windows-Yule et al. that segregation, the opposite of mixing, could be studied using PEPT in a vibrofluidized system under steady state conditions, as the authors were able to relate the residence time of the tracked particle to local compositions and in

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Nomenclature

Roman symbols

ff_c	flowability [−]
Fr	dimensionless Froude number [−]
g	gravitational acceleration [m/s^2]
M	mixing index [−]
P	overall fraction of a mixture component [−]
R	radius of mixing blade [m]
s	measured standard deviation from sampling [−]
s^2	measured variance from sampling [−]
t	time [s]
V_A	volume of particle type A [m^3]
V_S	sample volume [m^3]
x_{10}	particle size at 10% of the weighted particle size distribution, volume-based and, assuming constant particle density, also mass-based [μm]
x_{50}	weighted average particle size, volume-based and, assuming constant particle density, also mass-based [μm]
x_{90}	particle size at 90% of the weighted particle size distribution, volume-based and, assuming constant particle density, also mass-based [μm]

Greek symbols

ρ_b	bulk density [kg/m^3]
σ	true standard deviation from sampling [−]
σ_M	standard deviation due to measurement error [−]
σ^2	true variance [−]
σ_0^2	initial true variance [−]
σ_R^2	true variance for a completely random mixture [−]
φ_{eff}	effective angle of internal friction [°]
φ_{sf}	angle of internal friction at steady flow [°]
ω	rotational velocity of mixing blades [rad/s]

that way to determine mixing homogeneity [20,21]. However, in unsteady-state systems this relation can no longer be used [21], and in batch high-shear mixers it is therefore difficult to determine the overall state of mixing in the entire mixer i.e. the mixing homogeneity for the complete mixture, from these results. As mixing homogeneity is the dominant property determining the quality of most mixtures, they are evaluated based on this property, describing the quality of the mixture. Therefore, sampling is still a powerful and relevant tool as it can provide the information on the mixing homogeneity by calculating the differences in composition in each sample. Although mixing homogeneity, expressed in some form of mixing or segregation index, is studied using DEM as well, investigations in which DEM mixing homogeneity results are directly compared with experiments are scarcely found [22]. Sampling was therefore chosen in this work as the method to characterize mixing behavior experimentally by determining mixing homogeneity over mixing time for the entire mixer and to serve as validation data for DEM simulations in later papers.

Additionally torque measurements on a ribbon blade blender were conducted, using the required torque for mixing a specific granular mixture as a further parameter to characterize the effectiveness of granular mixing. Since the DEM method is based on the calculation of contacts forces for interactions between particles and between particle and the wall, the overall required torque can also be used as a further validation parameter for simulation results.

This work presents an experimental study of the characterization of mixing behavior in a twin helical ribbon blade blender using different cohesionless mixtures. These mixtures were chosen as a basis for later comparison with simple DEM simulations, which can later be extended for cohesive materials. Mixing homogeneity over time, determined by sampling, and the torque on one of the shafts are presented. Two model systems were tested; the first consisting of two size overlapping components, i.e. of similar size and size distribution, and the second consisting of two clearly differently sized materials, i.e. their particle sizes were completely separated. The influences of blade rotational speed and fill height on the development of mixing homogeneity and on torque in this mixer were studied.

2. Experimental method

2.1. Material and equipment

The materials used in this work for mixing homogeneity studies were differently colored plastic granules as the size overlapping model system and limestone particles in different size ranges as the differently sized model system, as shown in Fig. 1. The images in Fig. 1 are not at the same scale. Fig. 1a and b show microscopic images of the plastic granules (BASF, Germany) consisting of the same plastic material, but different in color. The differently colored plastic granules had overlapping particle size distributions, both distributions being roughly 200–1000 μm in size. The blue and orange plastic granules therefore each represented one of the components with particle size overlap in the first model system. Fig. 1c and d show limestone particles in two different size ranges, ordered from KSL Staubtechnik (Germany). Both limestone fractions were sieved into narrower fractions of 100–400 μm (fine) (1d) and 500–800 μm (coarse) (1c) respectively to produce different and separated fractions, using each fraction as one of the components of the second model system. For the torque measurements a third system of 3 mm spherical polyethylene particles was used as well (BASF, Germany), as shown in Fig. 1e and f. Size and shape distributions for all of these particle types were determined by a commercial image analysis setup (CamSizer, Retsch, Germany). All particles of the two model systems in the mixing homogeneity research were non-spherical and free flowing ($ff_c > 10$) for both limestone fractions and the plastic granules according to Jenike's classification for flowability [23,24]. Further frictional properties were determined considering the potential use of the experimental work here to be correlated with DEM studies. Frictional properties of the limestone fractions and plastic granules were measured in a Schulze type ring shear tester and are expressed as internal friction angle of the bulk instead of that of a single particle. In many DEM calibration studies frictional parameters are calibrated using a shear tester and bulk internal friction parameters or simply bulk shear stress at a given normal load, as may be found in e.g. [25–30]. The internal friction angles at $3 \cdot 10^3$ Pa normal load are reported in Table 1 and expressed as both effective angle of internal friction as is commonly used in bulk solids engineering [31] and as angle of internal friction at steady flow as this is the mode in a shear experiment that is often used for calibration of DEM parameters in literature, assuming no cohesion [25–29]. A detailed description of different friction angles may be found in the work by Schulze [24]. Details on the particle size distribution of each component, expressed in x_{10}, x_{50} and x_{90} values as well as further physical data on all materials discussed above are summarized in Table 1.

Mixing behavior was characterized in a 10 L vertical twin helical ribbon blade mixer (type HM 10 by Amixon, Germany), of which a top view is shown in Fig. 2a. and as briefly introduced in Simons et al. [32]. The ribbon blade mixer has 10 cm diameter blades; the distance between its shafts is 14.2 cm, allowing an overlap of the blades in the mixer center. A side view schematic in Fig. 2b shows the flow profiles of the material in the mixer. The material in the mixer is rotated due to normal and shear forces between the blades and the material. On top of the rotating mixing motion, the material to be mixed is conveyed up along the helical blades, indicated with the red arrows, and flows down near the shafts in the centers of the two helices, indicated by the blue arrows. An exchange of material takes place in the region