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Derivation of dimensionless relationships for the agitation of powders of different flow behaviours in a planetary mixer

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ABSTRACT

This study investigates the bulk agitation of free flowing or nearly cohesive granular materials in a pilot-scale planetary mixer equipped with a torque measurement system. Our major aim is to investigate the effect of the flow properties of several powders, as well as that of the set of experimental conditions (engine speeds N_R and N_G), on the power consumption of such a mixer. Thanks to a previous dimensional analysis of the system, this influence is studied through the variations of the power P with a characteristic speed u_{ch}, defined from engine speeds and geometrical considerations. Two relationships involving dimensionless numbers are derived to describe the agitation process: $N_{pG} = f\left(Fr_G, \frac{N_R}{N_G}\right)$ and $N_{pM} = f(Fr_M)$. For free flowing powders, a linear relationship is observed when plotting P against u_{ch}, and the resulting process relationship linking dimensionless numbers is $Np_M = 15{Fr_M}^{-1}$. In the more cohesive case, power values vary around an average value ($P = 54$ W) and the resulting process relationship is $Np_M = 1.8072{Fr_M}^{-1.467}$. It is argued that the exponent in the representation of N_{pM} against Fr_M may be a useful parameter for powder classification, and should be linked to powder rheometrical considerations.

1. Introduction

Powder mixing is an important unit operation in a wide variety of industries involved in solids processing. The end-use properties of products of the Pharmaceutical, Food, Plastic and Fine Chemicals Industries, often depend on process history which includes thermal and mechanical treatments in several unit operations (mixing, drying, grinding, crystallization, compression, encapsulation, agglomeration, etc.). These properties are usually determined through a formulation procedure involving costly evaluations of biological activity to determine the composition, dosage and form of a drug. Although constant efforts have been devoted to this aspect, little is known about the manufacturing process itself, which makes the study of mixing and mixtures a key subject for both academic and industrial product and process engineers [1–3].

When considering powder flow for mixing purposes, particulate systems are usually distinguished as either free flowing systems or cohesive systems, both categories that are arising according to the intrinsic particle characteristics, as well as to ambient factors. Particle size, particle shape, particle density, moisture, electrostatic charges, and temperature are indeed all affecting the mobility of individual particles, and at a higher level the bulk flow behaviour in such a way that it always dictates the choice of any mixing equipment. However, the mean particle size is always considered as the main criteria used to discriminate between these opposite behaviours.

- *Free flowing powders* typically have an average diameter higher than 100 μm. Particle–particle interaction forces are less important than gravity, resulting in a high individual mobility. Usually, no problem of particle agglomeration is detected in such systems. The counterpart is that particles of the same physical nature tend to follow the same paths within a mixer, so as to create local “condensation” of these in several regions inside the mixer. Most of the times, this segregation effect is resulting in out-specification of the final product, as well as strong process dysfunction. Convective mixers, consisting of a fixed drum in which a stirring device is put in a smooth rotating motion, are usually considered as the best viable mixer to handle free-flowing powders. The main reason lays in the ability of the stirrer to force the particles to visit mixer's region in which their self-organised segregative behaviour would have hardly allow them to transit.
- *Cohesive powders* are usually presented as particles of average diameter smaller than 50 μm. Strong particle interactions, such as van der Waals and electrostatic forces, enhanced by ambient factors, rather than gravity, govern particle flow. Agglomerates of particles of the same nature are therefore usually formed before mixing. It is more than often the case during mixing if this processing step is not intense enough to break the particle–particle “bounds”. The counterpart is this time advantageous, as once the mixture is achieved, the systems

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remain blocked and particle segregation can hardly take place. High-shear mixers consist of a bowl at the bottom of which a stirrer driven by a vertical shaft at up to 3000 rpm is placed. Together with some grinding equipment, high-shear mixers are considered as a reference to mix cohesive powders, because of their ability to break agglomerates. However, such types of equipment possess two major drawbacks: their relatively low capacity due to small filling ratios and their high specific energy consumption as compared to convective or drum mixers.

Companies having to process free-flowing powders and cohesive powders, as well as mixtures of both, are therefore in great need of a sort of universal mixing equipment, able to drive particles along relatively long distances, and also to provoke a local mixing intensification effect. Planetary mixers, defined as equipment combining dual revolution motion around two axes, certainly belong to this category of promising technology. Indeed, orbiting screw mixers have been studied and used in the industry for several decades now, but have failed to homogenize any type of particulate systems, in particular highly cohesive or strongly segregating systems. One reason may be that, due to the peripheral location of the screw, its pumping action on the powder bulk does not fully concern the particles which are located at the central core of the equipment.

Pioneer and more intensive works on non-conventional mixers, such as those conducted by Tanguy and co-workers in the mid-nineties, have been dealing mostly with miscible fluids [4–11] or foaming fluids [12]. From the different mixing technologies considered, the studied planetary mixer seems to be innovative enough to meet – at least partially – the need for a multi-task mixer. Originally built for operating with viscous fluids [9], this mixer has also achieved satisfactory mixtures of granular products [13], but lacks a deeper analysis of its agitation characteristics.

The design of mixer geometries and agitation devices is usually based on empirical methods [14], an idea that is definitely the rule when considering powder media. There is a real need to improve the basic knowledge on powder mixing systems and for this, the use of chemical engineering tools, such as correlations between dimensionless numbers, may significantly help [15–20]. Most of the studies reported in the literature so far, have been dealing with free-flowing systems, under the form of direct relationships between dimensionless numbers, without previous dimensional analysis. In addition, the difficulties in defining viscosity for particulate systems, and therefore a Reynolds number, have always driven us to consider correlations in which constant terms were powder-dependent. In direct analogy with the fluid case, authors have derived equations involving the Froude number (or rotational speed-based number) and either the Newton number (or any Torque-based number) or the power number (see Table 1).

Table 1
Some correlations derived in the literature for powder systems (A, B, K, m, n are powder-dependent constants).

Equipment type	Equation or relation type[a]	Ref.
Horizontal drum	$N_p = AFr^{-1} + B$	[19]
V-blender	$N_p = AFr^{-1} + B$ A and B are changing with time, as do the barycentre of the mixer.	[19]
Orbiting screw	$N_p = K(N_v/N_a)^m\ (L/D_v)^n$ N_v, N_a: rotational, orbital speeds – L, D_v: geometric characteristics	[20]
High-shear 3 blades/high angle	$N_p = AFr^{-1} + BFr^{-0.5}$	[16]
High-shear 2 blades/small angle	$N_p = AFr^{-1} + BFr^{-0.5}$ for $Fr < 4$ $N_p = AFr^{-1}$ for $Fr > 4$	[16]

[a] These relations have been re-written in terms of the power number rather than the Newton number.

It is also worth noting that the forms obtained for the high-shear mixer cases have recently been confirmed by Nakamura et al. [21] through DEM simulation, which means under free-flowing hypothesis.

Dimensional analysis governing power consumption and mixing time in this planetary mixer for the case of granular materials has been reported in one of our recent works [22]. This analysis led to the definition of the following dimensionless numbers:

$$N_{pG} = \frac{P}{\rho . {N_G}^3 . {d_S}^5} \tag{1}$$

$$Fr_G = N_G^2 \cdot d_s/g. \tag{2}$$

It has been shown that this set of numbers can be replaced by Np_M and Fr_M when a characteristic speed u_{ch} is introduced [10]. The advantage of this set of numbers is a reduction of the number of parameters because u_{ch} takes into account the contribution of the 2 operating rotational speeds (N_R and N_G) [10], which is a strong difference as compared to [20]:

$$N_{pM} = \frac{P}{\rho \cdot {u_{ch}}^3 \cdot {d_S}^2} \tag{3}$$

$$Fr_M = u_{ch}^2/(g \cdot d_s). \tag{4}$$

The expression of this characteristic speed u_{ch} has been established [10]. The choice of the relation depends on the value of the ratio N_R/N_G.
when

$$N_R \cdot d_s/(N_G \cdot D) \geq 1 : u_{ch} = (N_R \cdot D + N_G \cdot d_s) \tag{5}$$

when

$$N_R \cdot d_s/N_G \cdot D < 1 : u_{ch} = \sqrt{(N_R^2 + N_G^2) \cdot (d_s^2 + D^2)}. \tag{6}$$

The principal aim of this work is to study the agitation characteristics of different powder systems according to their cohesiveness in a planetary mixer. In particular, we will try different representations of the experimental results (dimensionless or not), so as to derive sound correlations within the idea of scale-up achievement of such mixers and comparison with the relations obtained in the literature.

2. Materials and methods

2.1. Mixing equipment

The planetary mixer used in this work is a TRIAXE® system (TriaProcess, France) which combines two motions: gyration and rotation (cf Fig. 1).

Gyration is the revolution of the agitator around a vertical axis while rotation is a revolution of the agitator around a nearly horizontal axis ($d_s = 0.14$ m and $D = 0.38$ m). This dual motion allows the agitator to cover the entire volume of the vessel. The mixing element of this mixer is a pitched four blade turbine and the axes of the two revolutionary motions are nearly perpendicularly driven by two variable speed motors. The mixing vessel is a stainless steel sphere, the blades of the agitator pass very close to the vessel wall at less than a millimetre.

The pumping effect of the agitator, which is responsible for convection in the volume it occupies, induces changes of direction almost continuously. When comparing the studied mixer to previous planetary mixers such as the orbital screw mixer, this point makes it a clear technological upgrade. Indeed, the mixing system becomes very effective at creating shear in the whole volume of the mixer, in probably a smarter way than classical high-shear mixers do in a much smaller volume and