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

C. Andre, Jean-François Demeyre, Cendrine Gatumel, Henri Berthiaux, G. Delaplace

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

C. André [a,b,*], J.F. Demeyre [c], C. Gatumel [c], H. Berthiaux [c], G. Delaplace [a]

[a] INRA, U.R. 638 Processus aux Interfaces et Hygiène des Matériaux, F-59651 Villeneuve d'Ascq, France
[b] UC Lille, Hautes Etudes Ingénieurs (H.E.I.), Laboratoire de Génie des Procédés, 13 Rue de Toul, 59046 Lille, France
[c] Université de Toulouse, centre RAPSODEE, Ecole desMines d'Albi-Carmaux, Campus Jarlard, 81013 Albi Cedex 09, France

A B S T R A C T

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.

Keywords:
Power consumption
Planetary mixer
Free flowing powder
Cohesive powder
Dimensional analysis

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

* Corresponding author at: INRA, U.R. 638 Processus aux Interfaces et Hygiène des Matériaux, F-59651 Villeneuve d'Ascq, France.
E-mail address: christophe.andre@hei.fr (C. André).

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:

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

$$Fr_G = N_G^2 \cdot d_s / g. \qquad (2)$$

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]:

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

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

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

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

when

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

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

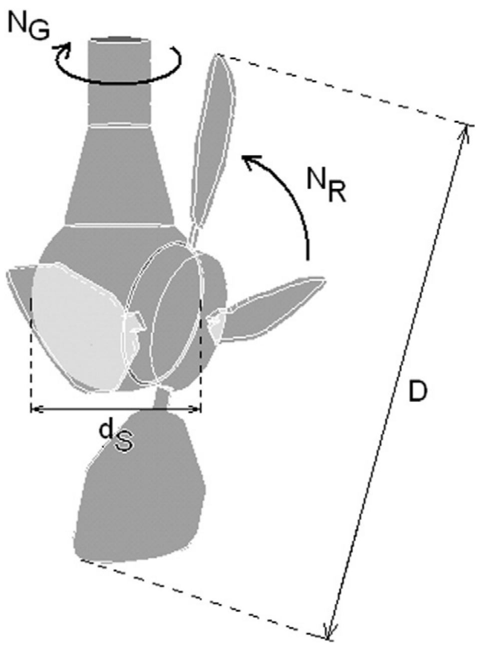

Fig. 1. Diagram of the TRIAXE® system investigated (d_s = 0.14 m and D = 0.38 m).

at a much higher energy cost. It is therefore suspected that such a mixer may be effective at mixing cohesive powders, as well as hard-to-mix particulate systems. However, the understanding of how the combination of both speeds of gyration and rotation affects the mixing process remains to be investigated.

For all the experiments, the apparent powder volume was a constant 48 l. The overall power P was determined using torque and impeller speed measurements. P refers to net power and is deduced from loaded power minus unloaded power (power monitored at the fixed impeller rotational speeds in an empty tank). The experimental set-up is shown in Fig. 2.

2.2. Particulate system involved

The solids used are free flowing (couscous and semolina) and nearly cohesive (lactose granulac 140) powders. The true densities of powders were measured with a Helium pycnometer (Accumulator Pyc 1330, Micromeritics) and the packed densities by a volumenometer. For the latter, a mass of powder is introduced into a graduated test-tube of 250 cm^3 and the bulk volume is recorded after a certain number of standard taps (500 taps). We can note that the true densities of the powders

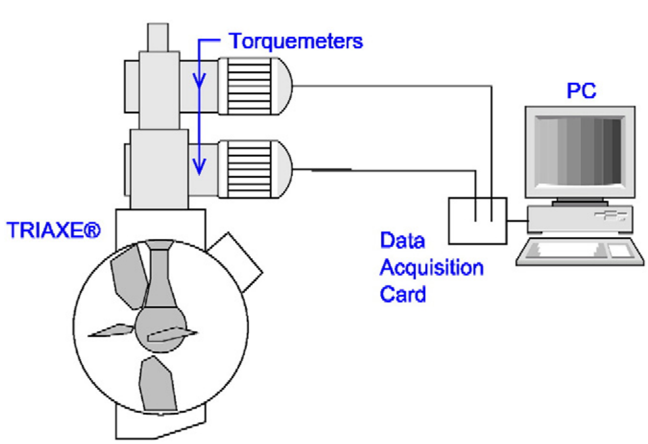

Fig. 2. Experimental set-up.

Table 2
Densities and properties of the powders.

Density (kg·l^{-1})	Semolina	Couscous	Lactose (Granulac 140)
True[a]	1.45	1.43	1.54
Aerated[b]	0.76	0.72	0.63
Packed (500 taps)[b]	0.82	0.76	0.90
Carr index	7.3%	5.3%	30%
Hausner ratio	1.08	1.06	1.43

[a] Established with the Helium pycnometer.
[b] Established with a volumenometer.

Table 3
Characteristic particle diameters of powders.

Diameter (μm)	Semolina[a]	Couscous[b]	Lactose granulac 140[a]
d_{10}	200	1100	20
d_{50}	340	1400	70
d_{90}	840	1800	140
Span = $(d_{90} - d_{10})$ / d_{50}	1.88	0.5	1.71

[a] Established with the laser particle-measurement instrument.
[b] Established by sifting.

are in the same range (see Table 2). From these values, the Carr index (IC) to evaluate the flowability [23] as well as the Hausner ratio (HR) to evaluate the compressibility of the powder [24] have been determined. It is widely admitted that free flowing powders have low IC (<18%) and low HR (<1.25). In contrast, more cohesive powders exhibit higher compressivity, therefore resulting in a higher IC (>20%) and higher HR (>1.4). In the present case, semolina and couscous are clearly free-flowing systems, while lactose has the characteristics of a cohesive system, probably without being fully cohesive as the HR remains close to the limit value of 1.4.

The particle size distribution of couscous was obtained by sieving using a Retsch® vibrating sieve, under defined conditions (mean amplitude and three minutes vibration). Sieving was performed using a standard set of sieves. The particle size distributions of semolina and lactose granulac 140 were obtained by LASER diffraction using a Mastersizer® particle size analyser operating in the dry mode (see Table 3: d_x is the particle diameter, for which x % of the particle size distribution has a diameter smaller than this value).

Table 4
Experimental conditions.

Run name	N_G (s^{-1})	N_R (s^{-1})
G100 R025	0.035	0.057
G200 R050	0.069	0.114
G400 R100	0.138	0.229
G800 R200	0.276	0.457
G025 R025	0.009	0.042
G050 R050	0.017	0.084
G075 R075	0.026	0.126
G100 R100	0.035	0.167
G200 R200	0.069	0.335
G400 R400	0.138	0.670
G600 R600	0.207	1.005
G800 R800	0.276	1.339
G025 R050	0.009	0.079
G050 R100	0.017	0.157
G100 R200	0.035	0.314
G200 R400	0.069	0.629
G400 R800	0.138	1.258
G025 R100	0.009	0.152
G050 R200	0.017	0.304
G100 R400	0.035	0.609
G200 R800	0.069	1.217
G025 R200	0.009	0.299
G050 R400	0.017	0.598
G075 R600	0.026	0.898
G100 R800	0.035	1.197

Table 5
Experimental results.

Run name	u_{ch} (m s^{-1})	$P_{lactose}$ (W)	$P_{semolina}$ (W)	$P_{couscous}$ (W)
G100 R025	0.027	56	16	15
G200 R050	0.054	69	34	33
G400 R100	0.108	79	72	76
G800 R200	0.216	90	149	163
G025 R025	0.017	34	9	9
G050 R050	0.035	36	19	18
G075 R075	0.052	42	29	28
G100 R100	0.069	44	39	38
G200 R200	0.138	53	83	82
G400 R400	0.277	67	172	173
G600 R600	0.415	79	250	245
G800 R800	0.554	95	331	364
G025 R050	0.032	23	17	16
G050 R100	0.064	30	34	33
G100 R200	0.128	41	73	70
G200 R400	0.256	50	153	148
G400 R800	0.513	82	296	309
G025 R100	0.062	20	32	30
G050 R200	0.123	32	68	64
G100 R400	0.247	46	143	136
G200 R800	0.494	74	281	286
G025 R200	0.121	25	66	61
G050 R400	0.242	47	138	132
G075 R600	0.364	57	214	200
G100 R800	0.485	69	280	273

Mixing experiments were carried out for various ratios of gyrational and rotational speeds. The ratios are represented as shown in the first column of Table 4. G100R200 refers to a mixing process performed with gyrational and rotational speeds of 10% and 20% of full speed range, respectively.

3. Results and discussion

Raw experimental results are presented in Table 5 under the form of the power measured according to the different run names. The characteristic speed has also been calculated.

The influence of the speed's combination was studied for all particulate systems through the observation of the evolution of the power P versus the characteristic speed u_{ch}, as shown in Fig. 3. For the free flowing systems (couscous and semolina), a linear relationship is observed and a unique curve is obtained whatever the powder considered. In the more cohesive case, a completely different representation is obtained, as power values fluctuate around an average: $P_{lact} = 54$ W. At low characteristic speeds ($u_{ch} < 0.08$ m s^{-1}), important fluctuations of power can be detected for the case of the more cohesive powder. The characteristic speed is probably too small to induce a generalized shear stress, so that particle–particle arches re-form them after the blade has passed. Conversely, through higher characteristic speeds, the whole bulk of lactose is put in motion thanks to the nearly mechanical fluidisation, the intensity of these interparticle cohesion forces decreases and the required power remains constant.

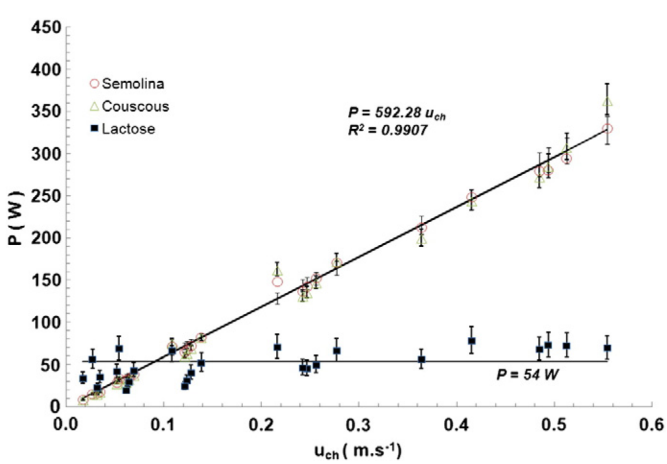

Fig. 3. Evolution of P against u_{ch}.

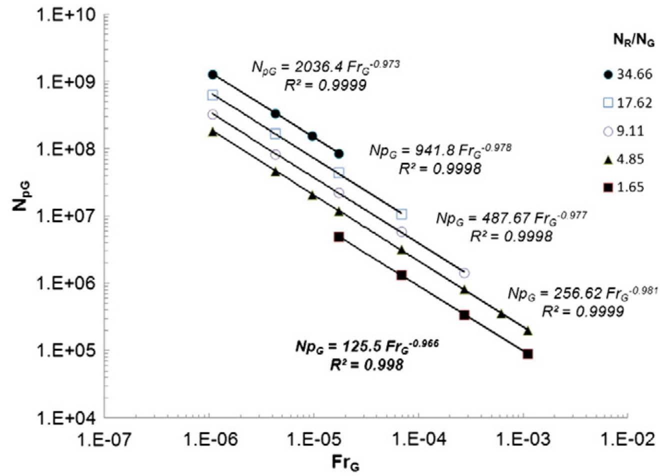

Fig. 4. Evolution of N_{pG} against Fr_G for semolina.

Figs. 4 and 5 show the evolution of N_{pG} against Fr_G for semolina and couscous in a log–log representation so as to put an emphasis on any power-type relationship. Each symbol represents a different speed ratio. These graphs demonstrate that the speed ratio and the Froude number have a strong influence on the mixer's power consumption. For a fixed value of the speed ratio, the exponent of the power law is close to −1. This value is in agreement with previous results [22].

In contrast, it is shown in Fig. 6 that the consideration of modified Froude Fr_M and Power Np_M numbers, leads to a single power characteristic for the mixing system when used to agitate free-flowing powders. Indeed, the two powders (couscous and semolina) exhibit the same behaviour, d_p appearing as a non-factor in these experiments. This result ascertains that u_{ch} governs the powder flow through a unique power law relationship with an exponent close to −1. This exponent is a direct consequence of the linear behaviour of P versus u_{ch} (see Fig. 3).

For free-flowing systems, experimental results are therefore described by the relation:

$$Np_M = 15 {Fr_M}^{-1}. \tag{7}$$

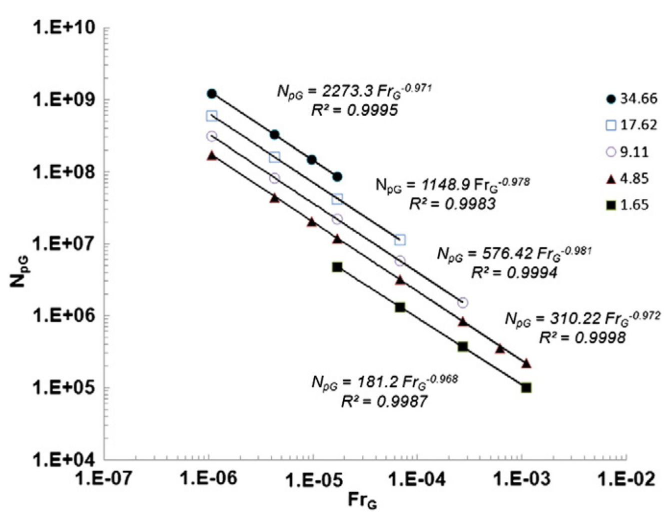

Fig. 5. Evolution of N_{pG} against Fr_G for couscous.

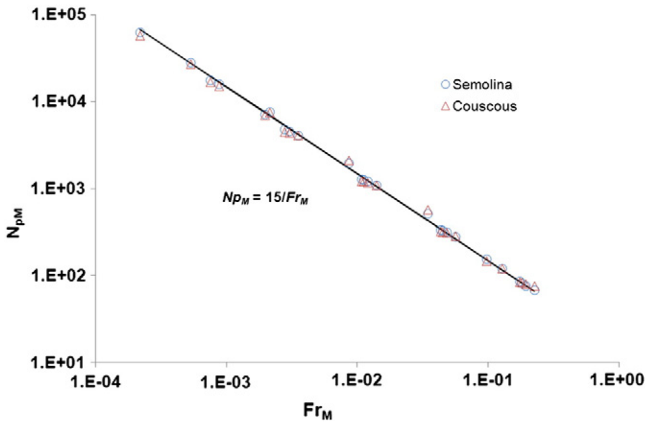

Fig. 6. Evolution of N_{pM} against Fr_M for semolina and couscous.

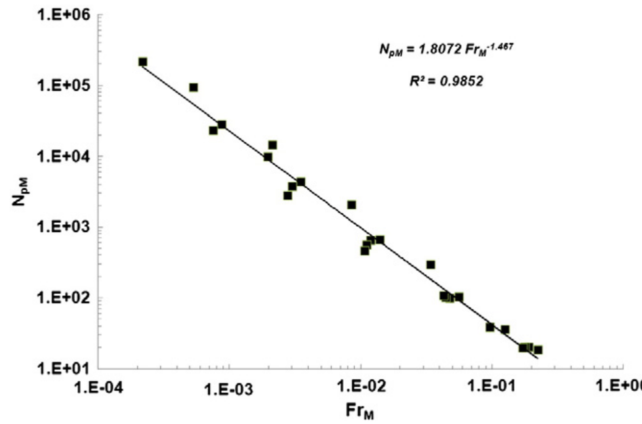

Fig. 8. Evolution of N_{pM} against Fr_M for lactose.

The constant number equal to 15 appearing in Eq. (7) does not depend on the particle size, but may be dependent on particle density as these are approximately the same for both products. It can also be claimed that particle–wall friction may be hidden in that number, as well as geometrical factors. This relation is similar to those obtained in the literature in rotating drums, and for which it can be suspected that unloaded power is hidden behind constant B, as well as high-shear mixers for high Froude numbers (>4). The agitation regime obtained in this mixer is comparable to that obtained in traditional high-shear equipment, but for Froude numbers smaller by several orders of magnitude. Unfortunately, no comparison can be made with the orbiting screw planetary mixer, because the representation chosen in [20] in terms of speed ratio does not allow it.

Fig. 7 shows the evolution of N_{pG} against Fr_G for the more cohesive powder (lactose) at fixed values of N_R/N_G. In contrast to the previous case, a unique curve is obtained whatever is the value of the speed ratio N_R/N_G. Indeed, this ratio is not a key parameter as power values were much less affected by operating conditions (N_R, N_G).

Fig. 8 shows the evolution of N_{pM} against Fr_M for the cohesive powder. The process relationship is now:

$$Np_M = 1.81\,{Fr_M}^{-1.467}. \tag{8}$$

The exponent of the power law is equal to −1.47 close to −1.5. The limit value of −1.5 corresponds to a theoretical case where the power is constant and independent of operating conditions.

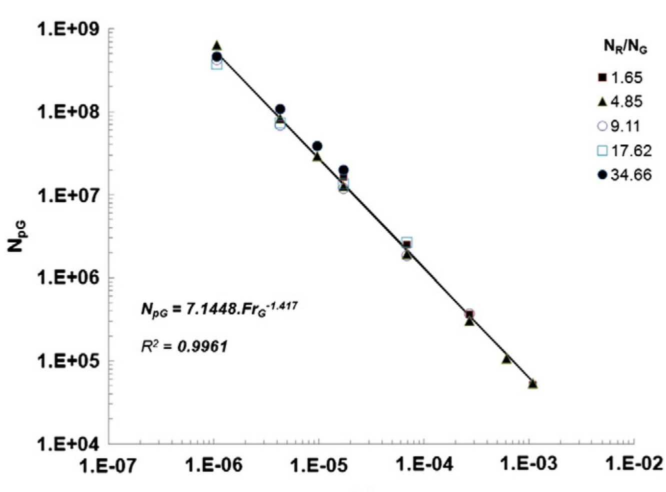

Fig. 7. Evolution of N_{pG} against Fr_G for lactose.

This relationship is clearly different from the one obtained with free-flowing systems in the same mixing equipment, as well as those obtained in the literature so far. It characterizes the flow behaviour of the particulate system, at a macroscopic rheological level.

4. Conclusions

This work shows that power consumption is strongly correlated with the type of powder investigated (free flowing or approaching cohesion). Modified Froude and power numbers for a planetary mixer proposed in [22] were used. These are a generalization of the well-known Froude and power numbers considered to describe conventional mixers. This study confirms that u_{ch} governs transport phenomena involving granular media as seen with other mixing processes involving gas/liquid [12], miscible viscous liquids [10,11] and granular medium [22] for planetary mixers.

As such, it was shown that dimensional analysis is a powerful tool for studying such correlations. More precisely, the exponent of the representation of N_{pM} against Fr_M is a useful parameter for powder classification. A value equal to −1 seems to correspond to free flowing behaviour, while a value close to −1.5 is an indication of a more cohesive behaviour. In future work, we will study other particulate systems, and in particular different cohesive powders. In addition, we will focus on the scale-up of such mixers by studying dynamic and kinematic similarities in this system.

Symbols used

d_p	diameter of powder, m
d_s	diameter of horizontal part of planetary mixer, m
D	diameter of turbine part, m
g	gravitational acceleration, m s^{-2}
N_G	gyrational speed of agitator, s^{-1}
N_R	rotational speed of agitator, s^{-1}
P	power, W
u_{ch}	maximum tip speed of agitator, m s^{-1}

Greek letters

ρ	density of mixed medium, kg m^{-3}

Dimensionless numbers

Fr_G	Froude number based on gyrational speed of agitator
Fr_M	generalized Froude number based on tip speed
N_{pG}	power number based on gyrational speed of agitator
Np_M	generalized power number based on tip speed

Acknowledgements

The authors thank Sara Quinger for the correction of the English spelling or grammatical errors.

References

[1] In: N. Harnby, M.F. Edwards, A.W. Nienow (Eds.), Mixing in the Process Industries, Butterworths, London, 1985, pp. 42–61.
[2] M. Poux, P. Fayolle, J. Bertrand, D. Bridoux, J. Bousquet, Powder mixing: some practical rules applied to agitated systems, Powder Technol. 68 (1991) 213–234.
[3] J. Bridgwater, Mixing of particles and powders: where next? Particuology 8 (2010) 563–567.
[4] P.A. Tanguy, F. Bertrand, R. Labrie, E. Brito De La Fuente, Numerical modelling of the mixing of viscoplastic slurries in a twin blade planetary mixer, Trans. IChemE 74 (Part A) (1996) 499–504.
[5] P.A. Tanguy, F. Thibault, C. Dubois, A. Aït-Kadi, Mixing hydrodynamics in a double planetary mixer, Trans. IChemE 77 (Part A) (1999) 318–323.
[6] M. Landin, P. York, M.J. Cliff, R.C. Rowe, Scaleup of a pharmaceutical granulation in planetary mixers, Pharm. Dev. Technol. 4 (1999) 145–150.
[7] G. Zhou, P.A. Tanguy, C. Dubois, Power consumption in a double planetary mixer with non-Newtonian and viscoelastic material, Trans. IChemE 78 (Part A) (2000) 445–453.
[8] T. Jongen, Characterization of batch mixers using numerical flow simulations, AIChE J 46 (2000) 2140–2150.
[9] G. Delaplace, L. Bouvier, A. Moreau, R. Guérin, J.C. Leuliet, Determination of mixing time by colourimetric diagnosis—application to a new mixing system, Exp. Fluids 36 (2004) 437–443.
[10] G. Delaplace, R. Guérin, J.C. Leuliet, Dimensional analysis for planetary mixer: modified power and Reynolds numbers, AIChE J 51 (2005) 3094–3100.
[11] G. Delaplace, R.K. Thakur, L. Bouvier, C. André, C. Torrez, Dimensional analysis for planetary mixer: mixing time and Reynolds numbers, Chem. Eng. Sci. 62 (2007) 1442–1447.
[12] G. Delaplace, P. Coppenolle, J. Cheio, F. Ducept, Influence of whip speed ratios on the inclusion of air into a bakery foam produced with a planetary mixer device, J. Food Eng. 108 (2012) 532–540.
[13] J.F. Demeyre, Caractérisation de l'homogénéité de mélange de poudres et de l'agitation en mélangeur Triaxe, PhD Thesis Report Institut National Polytechnique de Toulouse, France, 2007.
[14] L.T. Fan, Y.M. Chen, F.S. Lai, Recent developments in solids mixing, Powder Technol. 61 (3) (1990) 255–287.
[15] Y.L. Ding, R.N. Forster, J.P.K. Seville, D.J. Parker, Scaling relationships for rotating drums, Chem. Eng. Sci. 56 (2001) 3737–3750.
[16] P.C. Knight, J.P.K. Seville, A.B. Wellm, T. Instone, Prediction of impeller torque in high shear powder mixers, Chem. Eng. Sci. 56 (2001) 4457–4471.
[17] K. Miyanami, in: Linoya, Gotoh, Higashitani (Eds.), Mixing Powder Technology Handbook, 1991, pp. 595–612.
[18] M. Sato, Y. Abe, K. Ishii, T. Yano, Power requirement of horizontal ribbon mixers, J. Powder Technol. Jpn. 14 (1977) 441–447.
[19] M. Sato, K. Miyanami, T. Yano, Power requirement of horizontal cylindrical mixer, J. Powder Technol. Jpn. 16 (1979) 3–7.
[20] W. Entrop, Proc. European Conference on Mixing in the Chemical and Allied Industries, Mons, Belgium, D1, 1978, pp. 1–14.
[21] H. Nakamura, Y. Miyazaki, Y. Sato, T. Iwasaki, S. Watano, Numerical analysis of similarities of particle behavior in high shear mixer granulators with different vessel sizes, Adv. Powder Technol. 20 (5) (2009) 493–501.
[22] C. André, J.F. Demeyre, C. Gatumel, H. Berthiaux, G. Delaplace, Dimensional analysis of a planetary mixer for homogenizing of free flowing powders: mixing time and power consumption, Chem. Eng. J. 198–199 (2012) 371–378.
[23] H. Hausner, Friction conditions in a mass of metal powder, Int. J. Powder Metall. 3 (1967) 7–13.
[24] R.L. Carr, Evaluating flow properties of solids, Chem. Eng. 18 (1965) 163–168.