Batch mixing study of granular agro-food materials in an innovative mixer: the Triaxe®.

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Abstract
The object of this work is to characterize the operation of a new powder mixer, the Triaxe® for which systems with free flowing and cohesive media are studied. We show that this mixer, that combines two motion of agitation, is a very low energy consumer one, in particular for cohesive powders. The influence of the combination of gyrational and rotational speeds is particularly studied. The results are expressed in term of effective torque and power consumption.
Key-words
Mixing, Granular Systems, Dimensionless number, Power Consumption.

Contents

Introduction

In the every day life we are consuming blended solid products as pharmaceuticals and food. The end use properties of these products are more and more complex as they are covering more and more functions. Mixing is the main operation which permits to formulate these products, and therefore guarantee their properties.

In spite of these considerations, different mixer geometries and agitation devices exist but they are nearly always conceived by empiric methods, as well as they induce a systematic motion which do not allow the achievement of a good mixture at a fine scale. For instance, the use of chemical engineering tools, such as correlations between dimensionless numbers, ought to be considerable. But conversely to the case of fluids, the complexity of powder or grains does not enable to define properly the viscosity of the system.

For instance, the traditional methods of dimensional analysis, that always includes a Reynolds number, is difficult to derive. For this reason, empirical correlations between dimensionless numbers (generally the number of power, Np and the number of Froude, Fr), in which bulk powder flow characteristics in the mixer under consideration are included through constants, have always been used in the literature. To argue this, one may refer to the general paper by Miyanami (1991) the correlations of sato & al. for an horizontal drum mixer in Sato et al. (1977) or a ribbon mixer in Sato et al. (1979), the relations of Entrop (1978) for a screw mixer, of Werther (1976) for a fluidized bed.

In addition, particulate systems are classified according to several properties that may be defined at various scales: size and size distribution, shape and shape distribution, aerated or tapped bulk density, true density... When considering powder flow for mixing purpose, two main categories of particulate systems are distinguished:

- Free flowing powders: their average diameter is generally higher than 100 µm. These powders are flowingt very easily and do not pose any problem of mottage. On the other hand, each particle has a strong individual mobility, that may correspond to a strong tendency to segregate within a mixture.
- Cohesive powders: their average diameter is in general lower than 30 µm. These powders have strong interparticle connections such as van der Waals forces or electrostatic forces..., which can involve the formation of agglomerates. If these may cause flow or storage problems, they do not have a really tendency to segregate once the mixture is achieved.

The choice of a mixer is therefore conditioned to the type of powders, the type of mixture (composition) at play. For instance, in the case of an emerging mixing technology, it is important to quantify the operation of the apparatus with powders of different types.

This work deals with an unconventional batch mixer, the Triaxe®, developed and sale by Hognon S.A. company. Originally built for operating with viscous fluids, this mixer showed its capability to realise good mixtures of granular products. It consists on a spherical tank in which the powder is agitated by the combination of the gyration of the shaft and a classical rotational movement of the helix. Rotation and gyration speeds are independently controlled, allowing numerous combinations. This should be able to enhance the mixing process to finally achieve an intimate mixing, at a small spatial scale and probably at the micro-mixing scale.

Our objective is to quantify the effectiveness of this mixer with agro-food granular systems in terms of homogeneity of the mixtures and characterisation of agitation. In this work, we focus on this last aspect by studying the power consumed by this mixer, according to the various operating conditions: combination of velocities and type of powder. Thanks to the measurements of the torque developed by each engine (gyration and rotation) we seek to establish correlations between numbers without dimension as the Froude and Power numbers. This may help to characterise the various modes of the mixer.

1 Materials and methods

1.1 Particulate systems used

The solids used are agro-food products of different flow properties: free flowing powders (couscous and semolina) as well as a cohesive powder (Lactose GranuLac 140).

1.1.1 Densities

The true densities of the semolina and the couscous were measured with the Helium pycnometer (Accumulator Pyc 1330, Micromeritics). The packed densities were measured by a volumenometer. In this one, a known powder mass is introduced into a graduated test-tube of 250 cm^3 and the bulk volume is recorded after a certain number of shocks (500 taps). We can note that the densities of the free flowing powders are very close (cf table 1).

Table 1: Various densities of the products

Density [$kg \cdot m^{-3}$]	Granulac 140	Semolina	Couscous
True	1.54	1.47	1.44
Aerated	0.63	0.76	0.72
Packed (500 taps)	0.90	0.82	0.76

From these values, we can determine the compressibility, or Carr index (cf table 2 on the next page):

$$\%comp = 100 \times \frac{\rho_{packed} - \rho_{aired}}{\rho_{packed}} \tag{1}$$

Table 2: Carr indices

Granulac 140	Semolina	Couscous
30 %	7.3 %	5.3 %

1.1.2 Porosities

Intragranular porosity represents the relative volume of the "vacuum" inside a particle. The determination of intragranular porosity was measured from the porosimeter with mercury (Autopore III, Micromeritics). No value of intragranular porosity was detected, neither for the semolina nor for the couscous.

Intergranular porosity can result from the above measurements (cf equation (2)). We can distinguish aerated porosity and packed (or tapped) porosity, the latter indicates the state of maximum compacity of the system without destroying the particles.

$$\epsilon = \frac{\rho_{true} - \rho_{apparent}}{\rho_{true}} \tag{2}$$

Table 3: Values of porosity for the three products

Intergranular porosity	Granulac 140	Semolina	Couscous
$\epsilon_{inter}(packed)$	0.42	0.44	0.47
$\epsilon_{inter}(aired)$	0.59	0.48	0.5

Again, porosities of the free flowing powders are very close. The cohesive system shows its difference by initially occupying a more important volume which does not resist to tapping (cf table 2 and table 3).In any case, the values of the aerated porosities are used as a point of comparison between the powders as the bulk inside a mixer should be aerated for a good mixture achievement.

1.1.3 Particle size distribution

The particle size distributions of couscous and semolina were measured by sieving with control of the amplitude and the duration on a standardized series of sieve. For lactose, it has been obtained by laser diffraction using a dry mode Malvern Mastersizer intrument. The results are given in table 4.

Table 4: characteristic particle diameters of semolina and couscous – $^{+}$established with the laser particle-measurement instrument – *established by sifting

Diameter [µm]	Granulac 140^{+}	Semolina*	Couscous*
d_{10}	20	200	1100
d_{50}	70	340	1400
d_{90}	140	840	1800
$Span = \frac{d_{90} - d_{10}}{d_{50}}$	1,71	1,88	0,5

1.2 Mixer used

The Triaxe®is a mixer made up of a spherical tank (cf figure 1 on the following page) and composed of two engines for the agitation of the mixtures:

- The lower engine involves the axis of gyration, for speeds ranging from 0 to 30 rpm. This vertical axis is centered in the tank. Gyration can be carried out clockwise and anti-clockwise direction.

- The higher engine involves the mobile of agitation, for speeds ranging from 0 to 100 rpm. The blades of the mobile describe a disc around the tilted axis of rotation of 15° compared to the horizontal one.

Each blade tilting compared to the plan described by the blades axes what introduces a third axis. The combination of stirring velocities and the slope of the blades must make it possible to vary the conditions of flow in order to obtain a satisfying mixture. Moreover, there are various types of blades: full, openwork or out of knives in order to adapt to different powder flow problems.

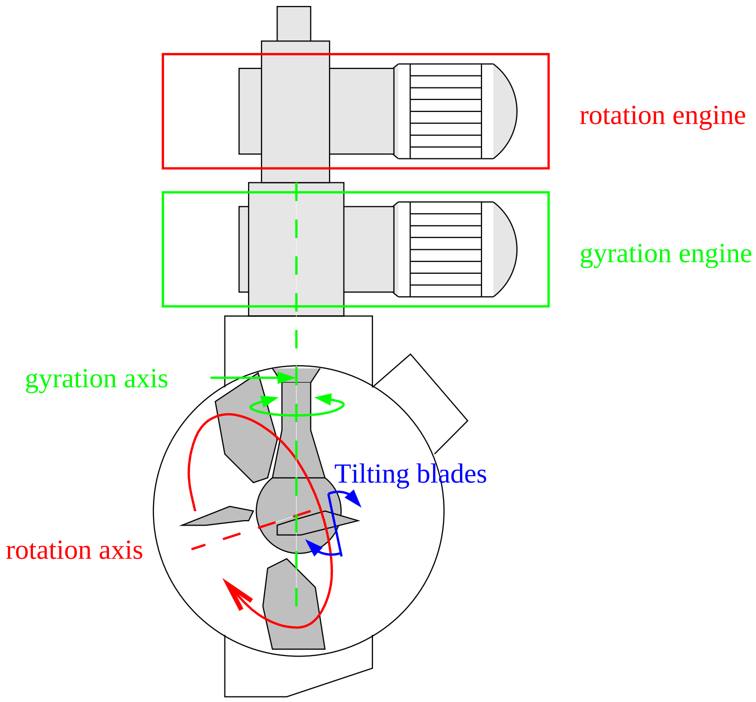


Figure 1: Sketch of the Triaxe®

The Triaxe® has two engines Sew Usocome of 370 Watts power. Each engine is controlled by a Movitrac. This turntable varies the frequency of the engine supply according to the tension which is applied, between 0 and 10 V. By measuring this tension, we determine the number of revolutions of the engines (cf figure 2).

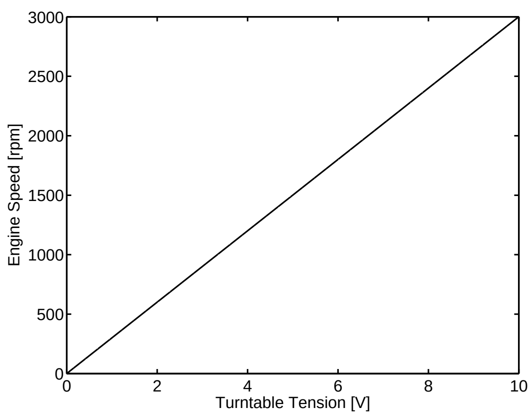


Figure 2: Calibration curve for the speeds of the engines

Knowing the reduction ratios at the exit of the engines, we deduce the speed of revolution from the axes of Gyration and of Rotation (cf equation 3)

$$N_{A_G} = \frac{N_{M_G}}{144.79} \quad \text{and} \quad N_{A_R} = \frac{N_{M_R} + 0.59 N_{A_G}}{34} \tag{3}$$

Where N_{M_G} and N_{M_R} are respectively the gyrational and rotational speeds of the engines.

Between each engine and the corresponding reducer, a rotary torquemeter of the society Scaime measuring the torque from 0 to 5 N·m has been placed. This allowed to know the power consumption of the two engines. The acquisition of these signals (voltage of each variator, torque developed by each engine) has been carried out thanks to a National Instruments card PCI-6023E. The data were collected thanks to the software LabVIEW 7.1, and then analyzed by the software Matlab.

The torque developed by each engine has been measured at the following speeds: 0, 75, 150, 225, 300, 450, 600, 900, 1200, 1800, 2400, and 3000 rpm. Also, we recorded points of measurements every 100 milliseconds on an interval of one minute to achieve the stability of the signal. The value of the torque used is the average of the acquired data. In order to obtain the value of the torque received by the agitated product, we carried out no-load tests. This allowed us to get free from the mechanical losses by cutting off the values from no-load test with those under loads:

$$T = T_{in\,load} - T_{no\,load} \tag{4}$$

The total useful torque is the sum of the useful torque measured on each axes. In the same way, the power consumption P_C is the sum of the useful output of Gyration P_G and of Rotation P_R:

$$P_C = P_G + P_R \tag{5}$$

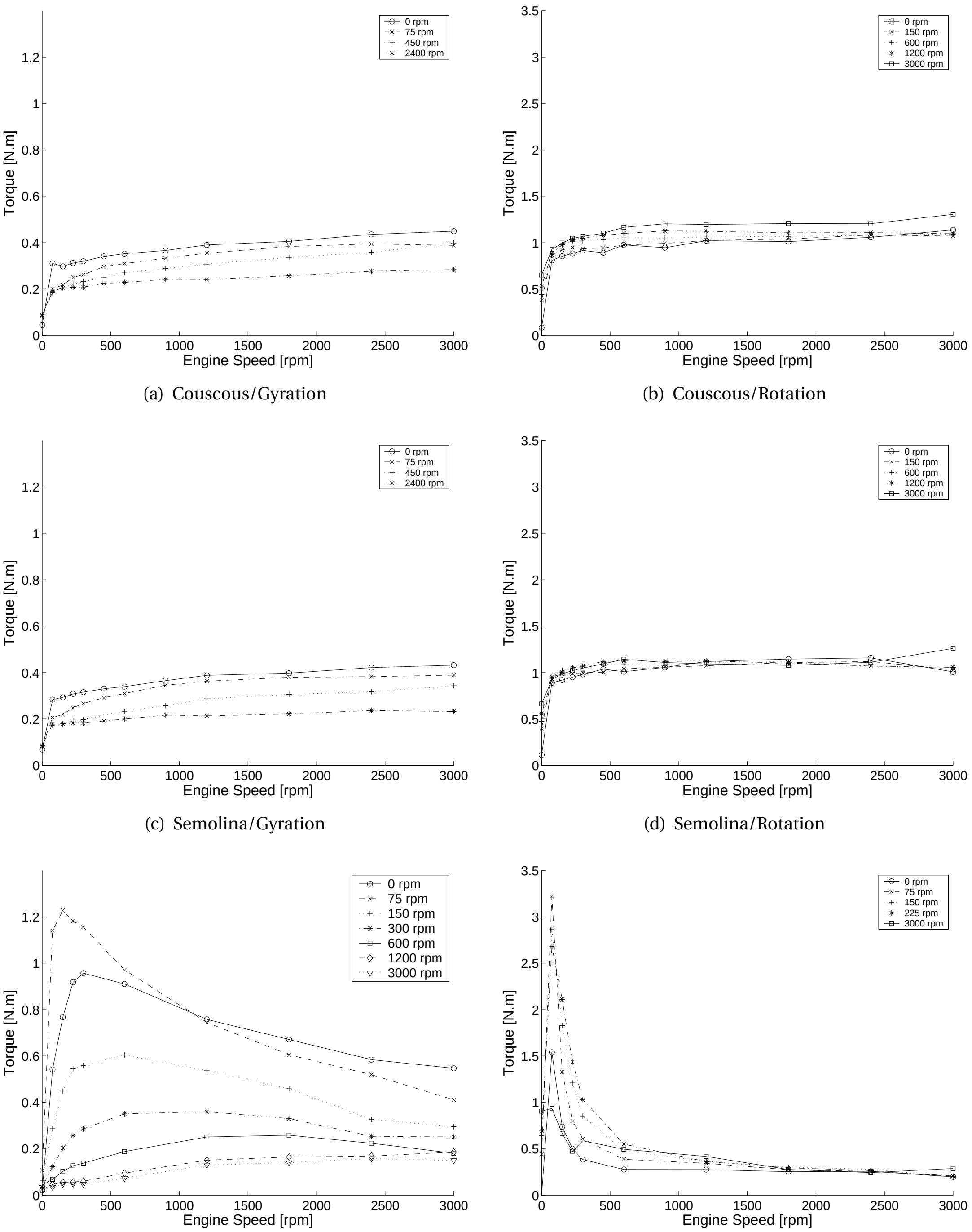
With $P_G = (T_G - T_{G_0}) \cdot 2\pi \cdot N_{M_G}$ and $P_R = (T_R - T_{R_0}) \cdot 2\pi \cdot N_{M_R}$. N_{M_G} and N_{M_R} are the speeds of the engines in round·sec^{-1}. Indeed, the torque is measured at exit of the engines and not on the gyration and rotation axes.

2 Results and discussions

The figure 3 on the following page gives the results of the measurements of the useful torque obtained on the two axes for tests on Couscous, Semolina and Lactose. Each graphics of figure 3 on the next page describes, for a couple Product/Engine, the useful torque developed by the engine according to its speed for various values of the speed of the other engine. For example, figure 3(a) on the following page describes the useful torque developed by the engine of Gyration for a test on Couscous. The various series of figure 3(a) on the next page correspond to various speeds of the engine of Rotation.

The analysis of this figure highlights that:

- The useful torque is mainly brought by the rotational movement. For same values of the engine speed, the useful torque brought by the engine of Rotation is approximately 3 times more important than the one brought by the engine of Gyration.
- In Rotation or Gyration, we always observe a phase of growth of torque with speed, and a plateau phase. For the cohesive powder, there exist a maximum between these two phases, corresponding to a critical speed.
- Once the lactose is in motion, it seems to be slightly fluidised, which decreases the interparticle cohesion forces. The torque required is therefore less important. This could explain why the measured torque decreases after the "critical engine speed".
- The torque developed by the engine of Gyration depends on the speed of the engine of Rotation. The higher the speed of the engine of Rotation, the lower the torque brought by the engine of Gyration. It may be argued that the torque brought by the engine of Rotation facilitates the displacement of the axes of Gyration within the product.
- On the other hand, for each speed of the engine of Gyration, the torque developed by the engine of Rotation is appreciably the same one.
- The maximum torque developed for the cohesive powder is more important than for the free flowing powders.



(a) Couscous/Gyration

(b) Couscous/Rotation

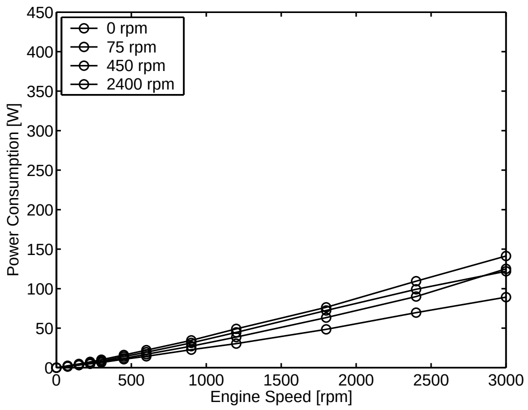
(c) Semolina/Gyration

(d) Semolina/Rotation

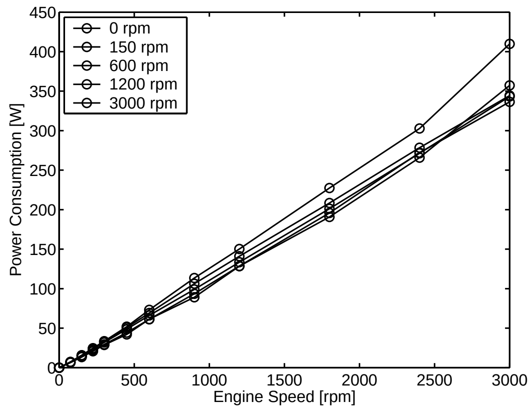
(e) Lactose/Gyration

(f) Lactose/Rotation

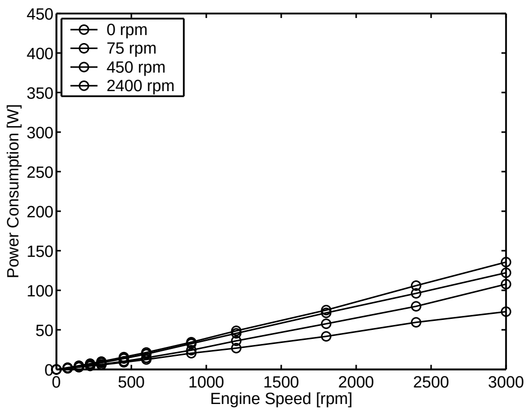
Figure 3: Torque measured on a driving shaft according to its speed. Each series corresponds to a speed of the other engine. Each graph corresponds to a couple product/engine



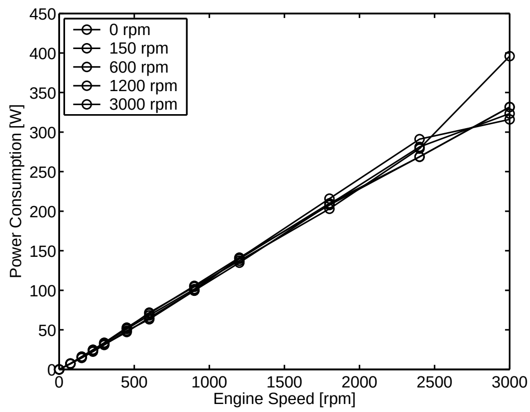
(a) Couscous/Gyration



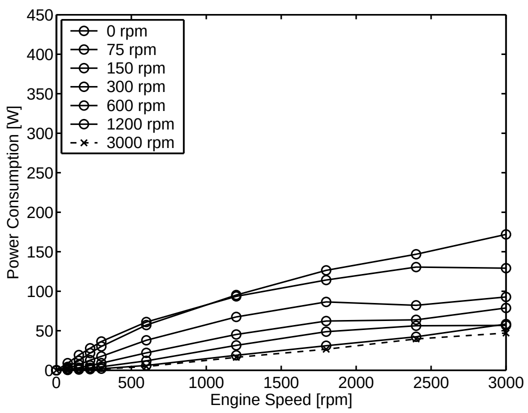
(b) Couscous/Rotation



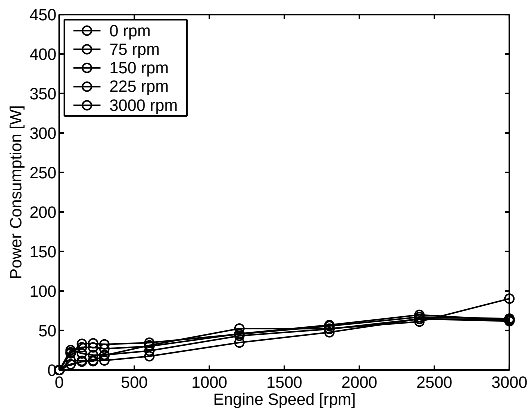
(c) Semolina/Gyration



(d) Semolina/Rotation



(e) Lactose/Gyration



(f) Lactose/Rotation

Figure 4: Effective power developed by each engine according to its speed. Each series corresponds to the speed of the other engine. Each graph corresponds to a couple product/engine

Each graphics of figure 4 on the preceding page describes, for a couple Product/Engine, the power consumed by the engine according to its speed for various values the speed of the other engine.

In the case of the free flowing powder, the power consumed by Rotation is three times more important than the power consumed by Gyration. There seems to exist a dependence of the power consumed by Gyration with respect to the speed of the engine of Rotation. On the other hand, for the cohesive powders, the power consumption by the engine of Gyration is slightly higher than that consumed by the engine of Rotation, especially for low speeds of the engine of Rotation. Indeed, in this case, the engine of Gyration must develop a maximum of power to put in motion the "block" formed by the cohesive powders.

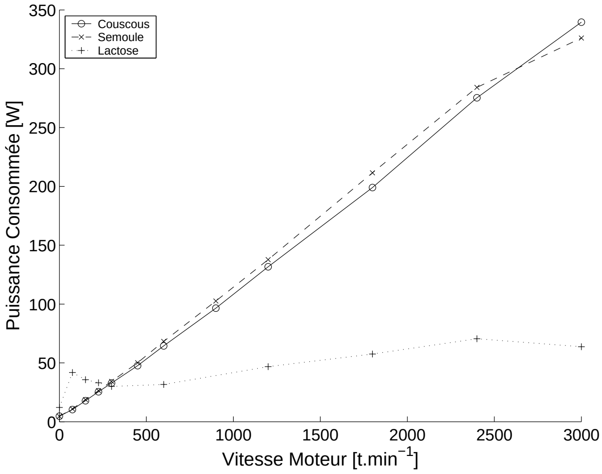


Figure 5: Comparison of the power consumption for the 3 products for a speed of Gyration of 150 rpm

The figure 5 represents the sum of the power consumption by the two engines for a speed of the engine of Gyration of 150 rpm. Its analysis shows that the power consumption for lactose is lower than that consumed for couscous or semolina after the "critical" speed of 150 rpm. Moreover, it is interesting to note that the mixer never consumed more than 450 W to put 48 litre of product into motion. We can estimate the specific power to be of the order of 15.6 W·kg^{-1} for couscous, 13.2 W·kg^{-1} for semolina and 5 W·kg^{-1} for lactose.

Conclusion

This work is completed on a batch mixer, the Triaxe®, developed and sold by the company Hognon SA. In this work, we are characterising agitation of particulate systems by studying the power consumed by this mixer according to the various operating conditions: combination of stirring velocities and type of powder. Thanks to measurements of the torque developed by each engine (gyration and rotation) we highlighted the existence a "critical" speed from which the forces of cohesions are overcome. This speed can be assumed to be a dynamic characterisation of the state of cohesion of the system. Thus, it would be very interesting to establish a comparison for various cohesive products between this one and an index characteristic of cohesion (for example the index of Carr or cohesion determined by the cell of Jenike or Schulze. . .). A short term objective is to determine an empirical relation between the Power number and the Froude number which characterise speeds of the two engines. In the longer term, this work on agitation will be connected to a study on the quality of the mixtures in term of homogeneity and of mixing time by on line image analysis method.

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