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Screening efficiency and rolling effects of a rotating screen drum used to process wet soft agglomerates

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Abstract - The rotating screen drums are largely used in most powder handling and processing industries. They are commonly used for size separation of granular materials. Objectives of the present work are to better understand both roles, screening efficiency and shaping effects and to investigate and model which process parameters are relevant when using an inclined rotating screen drum for processing wet couscous agglomerates. Durum wheat semolina was used as raw material to produce the wet agglomerates. The pilot rotating screen drum equipment was composed of two sieves to separate three fractions: fine, medium, and large agglomerates. The shaping effects of the rotating screen drum were evaluated from the measurements of the physico-chemical characteristics (size distribution, water content, compactness, and circularity) on wet soft agglomerates. To describe the screening efficiency parameters of a rotary screen drum, a specific method was developed by using a matrix analysis of the different measured weights of the collected products. The impacts of rotating screen drum parameters (angle of inclination, rotating speed, and product flow rate) on the sieving efficiency and on the shaping effects were investigated. The present results demonstrate high apparent screening efficiency of the rotating screen drum when used with wet agglomerates of durum wheat, ranging between 89 and 96% depending on the process conditions. Finally, using dimensional analysis, two correlations were proposed on the circularity and the apparent screening efficiency whatever the operating conditions used (drum speed, angle of inclination and feed rate).

Keywords - Rotating screen drum, durum wheat couscous, circularity, agglomeration mechanisms, dimensional analysis.

1. Introduction

The rotating drums are equipments largely encountered in process lines (both in continuous and batch modes) for handling and processing power and wet media. Indeed simple cylinders rotating about their central axis can be used in a horizontal position as batch drums, or as continuous drums when inclined at a few degrees to generate granular flows. The rotating drums are very versatile by realizing a large diversity of unit operations (e.g. solid-solid separation, mixing, drying, heating, chemical reactions, spraying, coating, granulation, screening, shape classification, etc.) in a large number of fields of application (e.g. environmental, chemical, mineral, metallurgical, food, pharmaceutical and civil engineering sectors, etc.). Different regimes for granular flow in rotating drums can occur (slipping, slumping, rolling, cascading, cataracting, and centrifuging modes) as a function of the process conditions, the regime type impacting on the process efficiency (Ding et al., 2001; Gray et al. 2001; Mellman, 2001; Spurling et al. 2001; Ding et al., 2002; Scott et al. 2009; Liu and Specht, 2010; Liu et al. 2013; Komosa et al. 2014).

Among the applications, the rotating screen drums are commonly used for size separation of granular materials. The rotating screen drums are relatively simple, low expensive, requiring little operating and maintenance costs compared to other separation systems. It consisted of a cylindrical perforated drum that rotated to perform size separation. Perforations or holes in the cylinder allow smaller materials to drop out during the rotation process. The fine particles are then first separated, at the beginning of the screening process. Due to the inclination of the drum, the remaining particles travel onward to the subsequent screening rings to be separated. Over-sized materials pass through the rotating screen drum. The flow of particles through the orifices on the rotating drum occurs due to the combination of the mobility of grains (like falling in avalanches, ballistic trajectory...) caused by the rotation regime of the drum and jamming in the vicinity of the orifices. The rotating screen drum can be managed by controlling the product flow, the driving speed and inclination angle of rotation axis (Prasanna Kumar, 2005; Chen et al 2010; Koprál et al., 2011). The screening efficiency was inversely proportional with the product flow rate and the drum rotational speed. An increase of the angle of inclination of the drum improves the screening efficiency, until a critical angle that generates too high horizontal motion velocity of the particles on the drum screen. The rotating screen drum can also classify particles of different shapes with different residence times of particles in the drum due to the particle shape (Furuuchi et al., 1993; Hartmann et al., 2006).

Attempts to predict performance of rotating screen drums still remain unsatisfactory due to a lack of understanding of the screening mechanisms when applied to continuous screening. Prasanna Kumar (2005) studied the effect of the various screen drum, grain and operating parameters on the flow rate of grains and developed empirical equations for the flow rate by dimensional analysis. The spacing between orifices, the diameter of orifice, the percent fill of drum and rotational speed of the drum significantly affect the screening flow rate. Comprehensive effect of granular flow under various operational parameters and screening methods are not yet been thoroughly understood, more particularly if the granular materials are characterized by heterogeneous size distribution (Liu, 2009; Chen et al., 2010). Some works have developed modelling by the dimensional analysis approach and proposed integrated models considering the equipment characteristics and the process conditions (Bongo Njeng, 2016, Prasanna Kumar, 2005).

The granular flow inside rotating drums may generate undesirable breakage or erosion of the granular material. These mechanisms were observed inside a rotary drum, due to impacts and wear with the drum walls and shear deformation within the granular material (Grant and Klamann, 2001, Ahmadian et al., 2011). The breakage trends of the grains were found to increase with rotational speed. Inside a rotary drum, granular material may experience impacts and wear with the drum walls and shear deformation within the powder bed. Knowledge of the powder dynamics remains essential to understand how particulate material breaks inside a drum.

In the food domain, the rotating drum screens are used for the manufacturing of the classical couscous grains. The couscous grains are made with durum wheat semolina, by the succession of four unit operations: wet agglomeration, rolling-sieving, steam cooking, and drying (Abecassis et al., 2012; Ruiz et al., 2014). At the end of the wet agglomeration stage, the soft wet agglomerates made of durum wheat semolina and water are continuously introduced inside an inclined rotating screen drum, constituted by successive screens of increasing meshes. This equipment is known to play two roles in the process of couscous grains. First the screening role, by separating the wet agglomerates according to their size, in order to only select those in the expected range of diameters (between 1 and 2 mm). It also contributes to the couscous grain structure, by modifying the shape and the density of the wet agglomerates due to the mechanical stresses that are promoted by granular flow inside the rotating drum. It is the rolling effects. The grains of couscous rolled in the rotary drum are more spherical and less porous, than those that are sieved on traditional horizontal vibrating

sieves (Hébrard, 2002; Abecassis et al., 2012). However, no scientific works have described the secondary agglomeration mechanisms that could occur on soft plastic grains during their flow inside a rotating drum. It should be noticed that on the current industrial lines, the rotating drum screens still generate large flow rates of under- and over-sized grains, after the wet agglomeration stage. These flows rates can represent more than 2.5 times the flow rate of target product. No study on the rolling stage during the process of the couscous grain has been yet conducted.

The objective of the present work is to develop an approach to better understand the two roles (screening efficiency and shaping effects) of the inclined rotating screen drum when used with the soft wet couscous agglomerates. Durum wheat semolina was used as raw materials to produce the wet agglomerates. The pilot rotating screen drum equipment was composed of two sieves to separate three fractions: fine, medium, and large agglomerates. The shaping effects of the rotating screen drum were evaluated from the measurements of the physico-chemical characteristics (size distribution, water content, compactness, and circularity) of the wet agglomerates, before and after processing by the rotating drum. The impacts of rotating screen drum parameters (angle of inclination, rotating speed, and product flow rate) on the sieving efficiency and on the shaping effects were investigated. A dimensional analysis approach is proposed to establish some relationships between the characteristics of the agglomerates and the process parameters. Experimental results give the very first tendency of this correlation.

2. Materials and methods

2.1. Raw materials

Durum wheat semolina of industrial quality (Panzani group, France) was used as raw material for the agglomeration experiments. Semolina was stored in hermetic containers at 4°C until experiments were carried out (less than 6 months). Semolina was first characterized using standardized methods. The water content of semolina (16.0 ± 0.5 g water / 100 g dry semolina) was determined according to the approved method 44-15A (AACC, 2000), by weighing after oven drying (RB 360, WC Heraeus GmbH, Hanau, Germany) at 105°C for 24 h. The characteristics values ($d_{10} = 66 \pm 1$ μ m; $d_{50} = 283 \pm 1$ μ m; $d_{90} = 542 \pm 4$ μ m) of particle diameter of semolina ($d_{50} = 283 \pm 1$ μ m) were measured by a laser granulometer (Coulter TMLS 230, Malvern, England) at room temperature. The diameter span $((d_{90}-d_{10})/d_{50})$ was

1.67. The semolina true density ($1.478 \pm 0.005 \text{ g.cm}^{-3}$) was measured by azote pycnometry. The total nitrogen content (TN) of semolina was determined by the Kjeldahl method, and the crude protein content (12.3 g protein/100 g dry matter) was calculated according to TN - 5.7 based on the AFNOR method V 03-050 (AFNOR, 1970).

2.2. Agglomeration process

The wet agglomeration process was conducted by using a horizontal low shear mixer. A sample of 5.0 kg of semolina was first introduced in the mixing tank (48.5 cm length, 20.0 cm width, and 19.0 cm height). The two horizontal shaft axes were positioned at 6.1 cm from the bottom of the tank, with 12 metal rotating paddle blades (47.5 cm length and 14.0 cm gap between 2 blades). The sample of semolina was mixed for 2 min at constant mixer arm speed (80 rpm) to equilibrate the temperature at $25^{\circ}\text{C} (\pm 2^{\circ}\text{C})$. Water was directly poured over the semolina under mixing at almost constant flow rate (8 g.sec^{-1}) during 2 minutes. Water addition was conducted to reach a final water content of 42.5 g water/100 g dry matter. After the water addition step, the mixture was stirred for 18 min to homogenize and agglomerate. The wet agglomerates were then collected using a plastic bowl and directly introduced in the rotating drum equipment.

2.3. Rolling processes

Experiments were performed in the rotating screen drum as illustrated in Fig. 1. It consisted of a cylindrical stainless-steel screening device (0.5 m diameter and 1 m total length) that rotated to perform rolling and size separation of the agglomerates. The cylinder was supported by a central axis and rotated by an electric motor and belt drive. The rotating screen drum consists of 2 successive joined cylindrical screening cylinders, each of 0.5 m height, having a 0.44 mm effective screening length (screen area = 69 cm^2). Sieve holes were round holes of 1 and 2.2 mm diameter. The ranges of experimental conditions were determined in regards with the capacities of the experimental equipment and with the values classically used in the industry. Different inclinations ($5.1, 6.2, 7.4, 9.7$, and 12.0°) and different angular rotating drum speeds: $0.21, 0.79, 1.36, 2.09$ and 2.72 rad.s^{-1} , which respectively correspond to: 2, 7.5, 13, 20, and 26 rpm, of the drum were tested. The wet agglomerates were continuously fed by using a vibrating feeder inside the rotating drum, tangentially to the bottom of the first screening ring. Different feed rates ($6.7, 11.4, 20.7$, and 25.3 g.sec^{-1}) were tested. Depending

on the operating conditions, the total time of the rolling/screening stage ranged between 10 and 15 minutes.

The fine agglomerates are first collected in a drawer under the first screen (1 mm). The medium agglomerates are collected in a drawer under the second screen (2.2 mm). The large agglomerates are discharged out of the drum and collected in a third drawer. For each experiment, the mass of the collected agglomerates in the three drawers was weighed.

2.4. Screening efficiency parameters of the rotating screen drum

To describe the screening efficiency parameters of a rotary screen drum, we have developed a specific method by using a matrix analysis of the different measured weights of the collected products. The method is based on the calculation of mass fractions (Fig. 2).

A mass (m^0) of the initial agglomerates is introduced in the drum. The rotating screen drum separates the initial powder in different products. The rotating drum is equipped by a number P of screens of increasing mesh. A number of $P+1$ products (i) is collected in the $P+1$ drawers. The mass (m_i) of each i collected product was measured in each drawer. The total mass of the collected products (m) is the sum of the masses (m_i) of the i products collected in the drawers. We supposed no mass accumulation inside the rotating drum ($m = m^0$).

We defined the mass fraction (x_i) for the product i , by the ratio of its mass (m_i) over the total mass (m) of collected product:

$$x_i = \frac{m_i}{m} \quad (1)$$

with: $\sum_{i=1}^{P+1} x_i = 1$ and: $m = \sum_{i=1}^{P+1} m_i$. The initial powder and the collected products are characterized by their fractions, according to the standard sieving procedure using a column of a number of N sieves of decreasing mesh (Fig. 2). A number of $N+1$ fractions (j) is characterized using the N sieves. The masses (m_{ij}) of each fraction j from each i product, are measured.

For the initial powder, we defined the mass fraction (x_j^0), by the ratio of the mass of its fraction j (m_j^0) over the total mass (m^0) of the initial powder:

$$x_j^0 = \frac{m_j^0}{m^0} \quad (2)$$

203

204 With: $\sum_{j=1}^{N+1} x_j^0 = 1$ and: $m^0 = \sum_{j=1}^{N+1} m_j^0$. For each i collected product ($\forall i \in \{1, \dots, P+1\}$),
 205 we defined three mass fractions (x_{ij} , y_{ij} and z_{ij}), by the ratio of the mass of their fraction j (m_{ij})
 206 over the different total masses: total mass of the collected products (m), total mass of the
 207 collected product in the drawer i (m_i), and total mass of the fraction j of all the collected
 208 product (m_j), respectively:

$$209 \quad x_{ij} = \frac{m_{ij}}{m} \quad (3)$$

$$210 \quad y_{ij} = \frac{m_{ij}}{m_i} \quad (4)$$

$$211 \quad z_{ij} = \frac{m_{ij}}{m_j} \quad (5)$$

212

213 with: $\sum_{j=1}^{N+1} \sum_{i=1}^{P+1} x_{ij} = 1$, $\sum_{i=1}^{P+1} x_{ij} = x_j$, $\sum_{j=1}^{N+1} x_{ij} = x_i$ and $m = \sum_{j=1}^{N+1} \sum_{i=1}^{P+1} m_{ij}$. Also: (i)
 214 $\forall j \in \{1, \dots, N+1\} \sum_{i=1}^{P+1} y_{ij} = 1$ and $m_i = \sum_{j=1}^{P+1} m_{ij}$, (ii) $\forall i \in \{1, \dots, P+1\} \sum_{j=1}^{N+1} z_{ij} = 1$ and
 215 $m_j = \sum_{i=1}^{P+1} m_{ij}$. This specific method is used to describe the screening efficiency of the
 216 rotating screen drum for wet agglomerates of durum wheat.

217

218

219 2.4. Characterization of the agglomerates

220 Water content - The water content (w) of agglomerates (dry base) was determined on 3-5 g
 221 samples, by a drying method in an oven (RB 360, WC Heraeus GmbH, Hanau, Germany) at
 222 105°C for 24 h (AACC Method 44-15A). Mean values were determined from triplicate:
 223 $w = m_w/m_s$, where w is the water content of agglomerates (g / g dry matter), m_w is the mass
 224 of water (g) and m_s is the mass of dry matter (g) in the sample.

225

226 Size distribution - A specific method was proposed to measure the distribution according to
 227 size criterion of the wet agglomerates. The size distribution was measured for the initial wet
 228 agglomerates (before introducing them in the rotating screen drum) and for the three products,
 229 that are collected after the rotating screen drum in the drawers. Size distribution was
 230 determined by sieving a sample of 100 g on the top of a column of 2 sieves of decreasing
 231 meshes (2 and 1 mm). The two sieves were chosen with almost similar meshes values,
 232 compared to the meshes of the two screens (1 and 2.2 mm) of the rotating drum.

233 The sieve column was mechanically mildly shaken using a rotachoc equipment (Rotachoc,
 234 Chopin Technologies, France) at 200 rpm for 5 min, to limit the particle breakage during the

mechanical shaking process (Saad et al., 2011). The possible broken effect is supposed similar for all the different products. The size distribution was obtained by weighing the mass of agglomerates on each sieve. The weight distribution according to size criteria was expressed as the percent of total weight. Measurements were conducted in triplicate.

Compactness - Samples of agglomerates (about 1 g) were used to determine the compactness, i.e. the solid volume fraction: $\phi = \rho_s / \rho_s^*$, according to Rondet et al. (2009). The solid apparent density ρ_s of the wet agglomerates was measured by using a hydrostatic balance with paraffin oil, which ensures the wet agglomerates without penetrating them. The solid true density ρ_s^* was measured by using a nitrogen pycnometer (ULTRAPYC 1200e, Quatachrom) after drying the agglomerates at 105°C for 24h.

Agglomerates shape - For each rolled product, we sampled a number of agglomerates (between 10 to 30) to be statistically representative of the shape of the sample. The selected wet agglomerates were dispersed on glass slides and observed by a camera (Lumix DMC-FS11, Panasonic, Tokyo, Japan). Image analyses were carried out with Fiji® software by following these steps:

- Image pre-treatment includes particle's border killing (removes particles that touch the border of the image), particle's silhouette hole filling (filling the holes within particle silhouette), separation function (breaks narrow isthmuses and separates touching particles), and morphological cleaning.
- Calibration step implies a translation from pixel unit into metric units.
- Measurements of the silhouette dimensions: Perimeter (P) and Area (A).
- The circularity shape factor is defined as the ratio of the perimeter of the silhouette (P) and the circumference of a disk that has the same area (A) as the silhouette. For a disk, circularity equals 1. Circularity value is lower than 1, when the projected shape of the particle departs from a disk, either because of a high roughness in particle surface or because of elongation. Circularity is equal to 0.89 for a square and to 0.50 for a long rectangle: $Circularity = P / 2\sqrt{\pi A}$. The presented values of the circularity shape factors were mean of the measured values.

2.5. Statistical analysis

The statistical significance of results was assessed using single factor analysis of variance (ANOVA). Multiple comparisons were performed by calculating the least significant difference using Microsoft Excel 2010, at a 5% significance level.

3. Experimental results

3.1. Shaping effects of the rotating screen drum

The characteristics of the wet agglomerates were determined immediately after the wet agglomeration stage, just before the introduction in the rotating drum (Table 1). The wet agglomerates are characterized by their water content (0.42), compactness (0.597), and weight distribution of the three fractions according to size criterion.

Physicochemical characteristics of the three fractions of the native agglomerates that were collected after the standardized method for the size distribution measurement were also measured (Table 1). It can be noticed the relatively low value of the mass fraction ($x_2 = 0.285$) for the medium initial agglomerates (between 1 and 2 mm). This low value is typical of the instantaneous agglomeration yield for the wet agglomeration operation, as usually observed during the industrial processing of the couscous grains (Abecassis et al., 2012).

It can be observed that the physicochemical characteristics of the wet agglomerates depend on their diameters. The large agglomerates are characterized by high water content (0.47) and low compactness (0.573). The small agglomerates are characterized by low water content (0.40) and high compactness (0.614). The dispersion of water content and compactness values according to the size of the agglomerates (Table 1) is typical of the growth mechanisms associated with the wet agglomeration process under low shear of wheat powders (Barkouti et al., 2012).

The shape description of the agglomerates was only conducted for the median fraction (1 mm < diameter < 2 mm), which is classically selected for the production of the couscous grains. The circularity value (0.636) typifies shape not totally spherical.

The present work has been conducted to investigate if the high water contents and the large dispersion of diameters measured for the wet agglomerates could favour (or not) the occurrence of specific mechanisms during the processing inside the rotating drum, with possible plastic strains under mechanical stresses, densification mechanisms under pressure, and potential difficulties in sieving mechanisms. Processing the initial wet agglomerates with

the rotating screen drum generates three rolled products by sieving mechanisms. The physicochemical characteristics of the three products have been determined (Table 2). Processing with the rotating screen drum slightly affects the characteristics of agglomerates. We observed slightly higher values of the water content for the agglomerates collected in the drawer 1 and drawer 2 after the rolling stage, when compared with the water content of the small and medium fraction in the initial wet agglomerates (Table 1). We could suppose that the rolling process induced erosion or breakage mechanisms of the large wet agglomerates that generated smaller agglomerates with high water content that are collected in the drawers 1 and 2. On the other hand, we observed lower values of the water content for the agglomerates collected in the drawer 3 after the rolling stage (0.434), when compared with the water content of the large fraction in the initial wet agglomerates (0.473) (Table 1). We can consider two hypotheses. Drying mechanisms could occur during the rolling process and impact all the agglomerates. The experimental results allowed observing a slight reduction of the global water content of the large agglomerates. We did not observe a reduction of the water content of the medium and small agglomerates, because of the fragmentation mechanisms of the large wet agglomerates, which compensate the drying mechanisms. The granular flow inside the drum could also promote agglomeration mechanisms with the adhesion of initial small and large agglomerates.

The rolling process does not impact the compactness values for the medium and large fractions of the agglomerates, as similar values were measured before and after the rolling process (Tables 1-2). We can suppose that the mechanical stresses generated by the shearing conditions of the granular flow inside the rotating drum is not enough sufficient to promote densification of the wet agglomerates of durum wheat. We measured slightly higher values of the compactness for the small fraction of agglomerates. This value is unusually high and could be partly explained by the method of the displaced volume in the paraffin oil, which is not well adapted to measure the solid volume fraction for the small agglomerates.

The shape characteristics of the rolled agglomerates were measured. The rolling process induces slightly higher values of circularity for the medium fraction (0.668), when compared with the initial wet agglomerates (0.636). We can suppose that the mechanical stresses generated by the rolling process could slightly impact the shape of the wet soft agglomerates through erosion or densification mechanisms and as a consequence increase their circularity.

3.2. Screening efficiency of the rotating screen drum

To describe the screening efficiency parameters of a rotary screen drum, we have developed a specific method by using a matrix analysis of the different measured weights of the collected products (Fig. 2). The mass fractions (x_{ij}) of the different collected agglomerates are first calculated over the total mass (m) of collected products (Table 3). We define the apparent screening efficiency of the rotating screen drum by considering the sum of the mass fractions of the diagonal of the matrix ($x_{11}+x_{22}+x_{33} = 0.923$), which indicates that 92.3% of the wet agglomerates are collected in the right drawer according to their size.

We define the global process efficiency by taking into consideration the mass fraction of the medium agglomerates ($j=2$) collected in the second drawer ($i=2$) ($x_{22}=0.332$), which indicates that 33.2% of medium agglomerates are produced by the agglomeration process and collected in the right drawer.

We define the impact of the processing inside the rotating screen drum on the size distribution of agglomerates, by calculating the relative difference of the mass fractions of the three classes of agglomerates (j) before and after processing ($100 (x_j - x_j^0) / x_j^0$). The present results (Tables 1-3) demonstrate a decrease of the mass fraction of the small agglomerates $j=1$ (-13.7%) and an increase of the mass fraction of the medium agglomerates $j=2$ (+26.0%). On the other hand, the processing inside the rotating screen drum does not affect the mass fraction of the large agglomerates $j=3$ (-3.9%)

We calculated the mass fractions (y_{ij}) of the different collected agglomerates, over the total mass (m_i) from the collected products in the drawer i (Table 4). We define the contamination rate of the collected product targets by taking into consideration the mass fraction of the small agglomerates ($j=1$) collected in the second drawer ($i=2$) ($y_{21}=0.115$), which indicates that 11.5% of products collected in the second drawer are too small in regards with the specifications.

We calculated the mass fractions (z_{ij}) of the different collected agglomerates, over the total mass (m_j) of the fraction j from all the collected products (Table 5). We define the loss rate of the targeted product by taking into consideration the mass fraction of the medium agglomerates ($j=2$) collected in the third drawer ($i=3$) ($z_{32}=0.074$), which indicates that 7.4% of the medium agglomerates are not collected in the right second drawer.

This original approach using matrix analysis has never been completed on an inclined rotating drum and allows us to characterize the overall process efficiency. The present work thus defines several parameters for evaluating the screening efficiency of the rotating screen drum: the apparent screening efficiency ($x_{11}+x_{22}+x_{33}$), the global process efficiency (x_{22}), the impact of the processing on size distribution of products ($100 (x_j - x_j^0) / x_j^0$), the contamination rate of the collected product targets (y_{21}), and the loss rate of the product targets (z_{32}).

3.3. Impact of the parameters of the rotating drum

We investigated the influence of the process parameters (angle on inclination, feed rate of wet agglomerates, and rotational speed) of the rotating screen drum on the screening efficiency parameters and on the impact on the characteristics of the rolled agglomerates. The results demonstrate monotonous variations of the experimental values when measured at the different values of the process parameters, even if the gap between the measured values is always not significantly different (Fig. 3-8).

Influence of the angle of inclination - An increase in the angle of inclination (from 5.1 to 12°) of the rotating drum induces slight changes of the screening efficiency parameters (Fig. 3). The description of the effects of the angle of inclination of the rotating drum can be divided in two parts on both side of the 6.2° angle. The higher values of the screening efficiency are observed at 6.2°, with 6.7% contamination rate and 6.7% loss rate, 39.7% apparent screening efficiency, and 93.6% global process efficiency. Beyond 6.2° of inclination, an increase in the angle of inclination until 12° of the rotating drum induces a decrease of the screening efficiency, with slight increases in the contamination rate and loss rate of the collected product targets and slight decreases in the apparent screening efficiency and global process efficiency. The lowest tested value of the inclination angle (5.1°) decreases the screening efficiency of the rotating screen drum, with high values of the contamination rate (17.1%) and loss rate (9.4%) of the collected product targets, and lower values of the apparent screening efficiency (88.7%) and global process efficiency (36.3%).

We evaluated the impact of the angle of inclination on the physicochemical characteristics of the agglomerates that are collected in the drawer 2 (Fig. 4). Angles of inclination between 6 and 12° of the rotating drum does not affect the water content, the compactness and the

circularity of the agglomerates. However, the lowest value of the inclination angle (5.1°) seems to generate a specific behaviour of the rotating screen drum, with slightly different measured values of water contents and compactness of the rolled agglomerated.

Influence of the feed rate - An increase of the feed rate (from 7 to 25 g/sec) inside the rotating drum only induces slight changes of the screening efficiency parameters (Fig. 5). An increase of the feed rate (from 7 to 17 g/sec) induces a decrease of the screening efficiency, with slight decreases of the apparent screening efficiency and global process efficiency and slight increases of the contamination rate and loss rate of the collected product targets. We do not observe significant changes of the screening efficiency parameters above a feed rate of 17 g/sec.

We evaluated the impact of the feed rate on the main characteristics of the collected agglomerates (Fig. 6). An increase in the feed rate does not impact the water content and the compactness of the collected product targets, but slightly increases the circularity (from 0.65 to 0.74) of the collected product targets.

Effect of the rotational speed - An increase of the rotational speed of the drum (from 2 to 27 rpm) induces changes of the screening efficiency parameters (Fig. 7). The lowest value of the rotational speed (2 rpm) generates a specific behaviour of the rotating screen drum, with high values of contamination rate and loss rate of the collected product targets, and low value of the apparent screening efficiency. Above a value of 7 rpm, we observe a slightly effect of the rotational speed on the screening efficiency parameters. An increase of the rotational speed induces a decrease of the screening efficiency, with slight decreases in the apparent screening efficiency and global process efficiency and slight increases of the contamination rate and loss rate of the collected product targets. The transport mechanisms and the sieving efficiency are then not affected by the rotational speed.

We evaluated the impact of the rotational speed rate on the main characteristics of the rolled agglomerates (Fig. 8). An increase in the rotational speed does not significantly affect the water content and the compactness of the collected product targets. We only observed that a slight increase the circularity (from 0.50 to 0.65).

4. Discussion

The present investigation allows describing the functional roles of the rotating screen drum during processing of wet agglomerates of durum wheat semolina. We try to evaluate the different mechanisms: screening, secondary agglomeration, erosion/breakage, and rolling (Iveson et al., 2001), that could be promoted as a function of the process conditions. However, it remains difficult to evaluate the specific contribution of each mechanism, by only using the measured values of weights and the calculated mass fractions and the hydrotextural state of the three classes of agglomerates (Ruiz et al., 2011; Barkouti et al., 2014).

4.1. Apparent screening efficiency

The main function of the rotating screen drum is to screen a mixture of granular objects (Chen et al., 2010). The present results demonstrate high apparent screening efficiency of the rotating screen drum when used with wet agglomerates of durum wheat (Table 3), ranging between 89 and 96% depending on the process conditions. These high values indicate the high performance of the rotating screen drum in regards with its primary function of size separation. The presence of low amounts of under sized agglomerates in the second and third drawer can be associated to screening deficiency, as these agglomerates could flow over the two first screens, until the next ones. The transport phenomenon is maybe too fast to allow the sieving function to fully occur. Erosion or breakage mechanisms could also partly explain the gap with full screening efficiency if mechanical conditions lead to attempt the strength yield of agglomerates (Rondet et al., 2013).

The apparent screening efficiency of the rotating drum is affected by the process parameters (Fig. 3, 5, and 7). An increase of the angle of inclination and of the rotational speed slightly reduces the apparent screening efficiency due to a faster flow of the agglomerates inside the drum, inducing lower residence times on each screen for the sieving function (Rotich et al., 2015). At too low rotational speed (2 rpm), the transport mechanisms and the sieving efficiency are also affected. An increase of the feed rates (until 17 g/sec) slightly reduces the screening efficiency due to a more important load of agglomerates inside the drum, which reduces the frequency of the contacts of agglomerates on the screens, and thus reduces their opportunity to be sieved.

These high performances could be discussed in regard to the relatively low value of the global process efficiency, with range between 32 and 37% as a function of the process conditions

(Fig. 3, 5, and 7). These values are associated to the global process efficiency of both the wet agglomeration operation and the rolling operation. Almost similar values are found on the process industrial lines (Abecassis et al., 2012). The first wetting and agglomeration operations are known to be at the origin of the low efficiency of the couscous grains production at industrial scale, which is observed after the rotating drum.

4.2. Impact on structuring mechanisms

The processing could generate specific mechanisms of secondary agglomeration and impact the mass fractions of the different collected fractions. The possible occurrence of secondary agglomeration was estimated by the changes of the values of the mass fractions of the collected small agglomerates, compared to the native mass fractions (Table 3) and also the hydrotextural analysis. The present study demonstrates very slight mechanisms of secondary agglomeration, with low decreases (between -13% and +2%) of the mass fractions of the small agglomerates, whatever the process conditions (data not shown). The agglomerates properties, the drum characteristics, and the process parameters do not allow generating enough efficient interactions between the soft agglomerates, to promote growing mechanisms by incorporating the small particles in larger agglomerates. Increasing the water content of the agglomerates and/or the mechanical stresses inside the drum could promote the secondary agglomeration mechanisms. In these conditions, the more plastic and sticky agglomerates could be involved in secondary agglomeration mechanisms under higher mechanical stresses. Moreover, if this phenomenon occurs, the resulting agglomerate will exhibit a mean hydrotextural state, between higher compactness/lower water content of the small particles and lower compactness/higher water content of the larger.

The impact of processing inside the rotating screen drum on the compactness and water content of the wet agglomerates can be discussed by using the hydro-textural diagram (Ruiz et al., 2011) (Fig. 9). This diagram is limited in its upper part by the saturation curve, which represents the maximum water content that a medium of a given constant compactness can contain. Before or after processing inside the drum, the increase in agglomerates size is concomitant with an increase in their water content and a decrease of their compactness. These relationships are similar to those obtained thanks to a classical wet agglomeration process (Rondet et al., 2010). Nevertheless, the agglomerates generated in this study and whatever the process parameters are found to be almost close to a water saturated state (Fig. 9). The rotating screen drum process does not significantly impact the hydro-textural

parameters of the wet agglomerates, because almost no secondary agglomeration phenomena occur. In fact, the present experiments were realized in a range of process parameters (rotation speed, angle of inclination, and product flow rate) accessible by the experimental equipment. We were not able to test wider conditions because of experimental limits connected to the too slow or too fast flow of the product inside the drum. A possibility to generate secondary agglomeration mechanisms could be to increase the water content of the agglomerates to modify their characteristics (plasticity, fragility, stickiness, etc.).

The powder flow inside the rotating drum could also induce some breakage and/or erosion mechanisms of the soft wet agglomerates. The occurrence of breakage and/or erosion was estimated by the changes of the values of the mass fractions of the collected large agglomerates, compared to the native mass fractions (Table 3). The present study demonstrates some mechanisms of erosion or breakage during processing, with decreases of the mass fractions of large agglomerates, which ranges between (between -4% and -40%) as a function of the process conditions (data not shown). The wet agglomerates of durum wheat do not resist to the mechanical stresses during processing inside the rotating screen drum (Rondet et al., 2013).

The rolling effects are associated with possible changes in the structure and shape of the wet agglomerates of durum wheat. The presented results do not demonstrated a significant effect of the rotating screen drum on the compactness and water content of the wet agglomerates of durum wheat. The mechanical stresses distribution is not enough high during the powder flow inside the drum to promote shear stresses higher than their plastic yield on the agglomerates and also reduce their internal porosity by compression. On the other hand, a slight increase in the circularity values of the wet agglomerates (Table 3) is observed after processing inside the drum. This increase in circularity could be associated to the loss of surface irregularities on the agglomerates, according to the erosion mechanisms. The circularity increase is favoured by increasing the feed rate (Fig. 6) or the drum speed (Fig. 8). The rolling effect of the rotating drum is classically reported under industrial conditions and greatly contributes to the final sensory attributes of the couscous grains (Abecassis et al., 2012).

4.3. Dimensional analysis

From the experimental study, we aimed in developing two empirical correlations gathering in two unique process relationships all the experimental circularity (CIR) and apparent screening efficiency ($ASE = x_{11} + x_{22} + x_{33}$) obtained whatever the operating conditions used (drum speed, angle of inclination and feed rate) by using the dimensional analysis. This approach makes it possible to reduce the number of variables describing a physical problem using a set of dimensionless ratios. The number of ratios originally used to describe the problem can be obtained from the Buckingham theorem (Buckingham et al. 1914).

The first step of dimensional analysis consists in establishing the list of relevant dimensional parameters as remembered in the book of Delaplace et al. 2015. In the case of rotating drum, the relevant dimensional parameters and their fundamental quantities are listed in Table 6. The Buckingham theorem states that any physically meaningful equation involving n variables expressible in terms of k independent fundamental quantities can be rearranged into an equivalent equation involving a set of $p = n - k$ dimensionless variables, which are derived as products of powers of the original variables. In our study, we have listed 9 variables (n) that can be expressed in terms of 3 fundamental quantities (k). Following the procedure described in the book of Delaplace et al. (2015), the dimensional matrix (not shown) can be obtained and permits to express the circularity and the screening efficiency according to 'p=6' dimensionless variables.

The two physical phenomena refer to the equation: $CIR = f(D, l, L_T, g, d_{50}, \rho, N, \alpha, D_b)$ and $ASE = f(D, l, L_T, g, d_{50}, \rho, N, \alpha, D_b)$. Applying Buckingham π -theorem, six dimensionless π -terms were obtained:

$$\pi_1 = \frac{D}{L_T} \quad (6)$$

$$\pi_2 = \frac{l}{L_T} \quad (7)$$

$$\pi_3 = \frac{d_{50}}{L_T} \quad (8)$$

$$\pi_4 = \frac{N}{D^{-0.5} \cdot g^{-0.5}} \quad (9)$$

$$\pi_5 = \alpha \quad (10)$$

$$\pi_6 = \frac{D_b}{\rho p \cdot D^{2.5} \cdot g^{0.5}} \quad (11)$$

The independent influences of the variation of each adimensional number on the value of CIR and ASE were studied. This analysis made it possible to observe that values can be mathematically described by:

$$CIR \text{ or } ASE = f(\pi_4 = \frac{N}{D^{-0.5}.g^{0.5}}; \pi_5 = \alpha; \pi_6 = \frac{Db}{\rho p.D^{2.5}.g^{0.5}}) \quad (12)$$

The levels of each independent parameter considered for the experiment are given below:

$$\pi_4 = 0.008, 0.028, 0.052, 0.075, 0.098$$

$$\pi_5 = 0.088, 0.129, 0.169, 0.209$$

$$\pi_6 = 0.000009, 0.000015, 0.000027, 0.000034$$

Fig. 10 depicts the adjustment between the values of the dimensionless circularity (CIR) and apparent screening efficiency (ASE) described by models and those experimentally obtained, whatever the process conditions. We found that the two proposed models (Eq. 13-14) describe rather well the evolution of the circularity and the apparent screening efficiency. Indeed, almost all experimental measurements are contained in a range corresponding to $\pm 20\%$ of the value predicted by the model.

$$CIR = 0.073.Ln(\pi_4) + 0.567.\pi_5^{0.081} + 0.621.\pi_6^{0.043} + 0.06 \quad (13)$$

$$ASE = 90.0.e^{(-0.05.\frac{\ln(\frac{\pi_4}{0.06})}{2.59})^2} \quad (14)$$

The values taken by Eq. 13-14 parameters make it possible to highlight the influence of process conditions. The circularity and the apparent screening efficiency are mainly affected by the drum speed and the angle of inclination. According to this mechanism, it has been possible to develop two original and descriptive models based on an adimensional approach. Unique equations were proposed whatever the process condition and are associated with sets of coefficients. In order to improve the physical understanding of the underlying phenomenon, an experimental approach specially designed to allow the establishment of regime maps through a physical approach and the identification of dimensionless numbers *e.g.* a ratio between a transport speed and a sieving speed could be further carried out. Nevertheless we can notice that it could be difficult to found explicit experimental conditions which lead to decrease the screening efficiency (less than 80%).

5. Conclusion

A matrix analysis allows describing the population balance of the mass sieved by a rotating screen drum and also taking into account the functional roles of operation during processing of wet agglomerates of durum wheat semolina. Results highlight that high apparent screening efficiency of the rotating screen drum ranging between 89 and 96% depending on the process conditions. These high values indicate the high performance of the rotating screen drum in regards with its primary function of size separation.

The rotating screen drum process does not significantly impact the hydro-textural parameters of the wet agglomerates as no secondary agglomeration phenomena significantly occur. A dimensional analysis is conducted to purpose relationships based, between the circularity on the one hand and the screening efficiency on the other hand and the process parameters. Nevertheless in order to improve the physical understanding of the underlying phenomenon, an experimental approach with more experimental points could be further carried out.

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Table 1. Physicochemical characteristics of the initial wet grains made of durum wheat semolina, just before the rolling process in the rotating drum.

	Mass fraction (x_i)	Water content (g / g dry matter)	Compactness (-)	Circularity (-)
Wet grains	--	0.420 (± 0.010) ^b	0.597 (± 0.006) ^b	--
Small fraction (diameter < 1 mm)	0.483 (± 0.026) ^b	0.398 (± 0.010) ^a	0.614 (± 0.004) ^c	--
Medium fraction (1 mm < diameter < 2 mm)	0.285 (± 0.066) ^a	0.408 (± 0.010) ^a	0.606 (± 0.005) ^{bc}	0.636 (± 0.140)
Large fraction (2 mm < diameter)	0.232 (± 0.052) ^a	0.473 (± 0.010) ^a	0.573 (± 0.011) ^a	--

Values are means ($\pm$ standard deviation).

Values in column with the same letter were not significantly different ($P < 0.05$).

Table 2. Physicochemical characteristics of the three classes of wet agglomerates of durum wheat semolina, collected after the rolling process.

	Water content (g / g dry matter)	Compactness (-)	Circularity (-)
Agglomerates in drawer 1 (d < 1 mm)	0.410 (± 0.005) ^a	0.654 (± 0.028) ^c	--
Agglomerates in drawer 2 (d < 2.2 mm)	0.425 (± 0.003) ^b	0.609 (± 0.060) ^b	0.668 (± 0.084)
Agglomerates in drawer 3 (2.2 mm < d)	0.434 (± 0.004) ^b	0.571 (± 0.020) ^a	--

Values are means ($\pm$ standard deviation).

Values in column with the same letter were not significantly different ($P < 0.05$).

Table 3. Calculated mass fractions (x_i and x_{ij}) of the collected agglomerates i and their fractions j , over the total mass (m) of collected product, after the processing inside the rotating screen drum.

	Agglomerates in drawer i=1 (d < 1 mm)	Agglomerates in drawer i=2 (d < 2.2 mm)	Agglomerates in drawer i=3 (2.2 mm < d)	Total collected agglomerates
Small agglomerates j=1 (d < 1 mm)	0.368	0.043	0.006	0.417
Medium agglomerates j=2 (1 mm < d < 2 mm)	0	0.332	0.027	0.359
Large agglomerates j=3 (2 mm < d)	0	0	0.223	0.223
Total collected agglomerates	0.368	0.375	0.256	1

Table 4. For each collected agglomerates i , calculated mass fractions (y_{ij}) of their fractions j , over the total mass of collected product in the drawer i , after the processing inside the rotating screen drum.

	Agglomerates in drawer $i=1$ ($d < 1$ mm)	Agglomerates in drawer $i=2$ ($d < 2.2$ mm)	Agglomerates in drawer $i=3$ (2.2 mm $< d$)
Small agglomerates $j=1$ ($d < 1$ mm)	1	0.115	0.023
Medium agglomerates $j=2$ (1 mm $< d < 2$ mm)	0	0.885	0.104
Large agglomerates $j=3$ (2 mm $< d$)	0	0	0.873
<i>Total collected agglomerates</i>	<i>1</i>	<i>1</i>	<i>1</i>

Table 5. For each fraction j , calculated mass fractions (z_{ij}) of their distribution in the drawer i , over the total mass of fraction j , after the processing inside the rotating screen drum.

	Agglomerates in drawer $i=1$ ($d < 1$ mm)	Agglomerates in drawer $i=2$ ($d < 2.2$ mm)	Agglomerates in drawer $i=3$ (2.2 mm $< d$)	<i>Total collected agglomerates</i>
Small agglomerates $j=1$ ($d < 1$ mm)	0.883	0.103	0.014	<i>1</i>
Medium agglomerates $j=2$ (1 mm $< d < 2$ mm)	0	0.926	0.074	<i>1</i>
Large agglomerates $j=3$ (2 mm $< d$)	0	0	1	<i>1</i>

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Table 6. Definition of the starting variables and fundamental quantities used for the dimensional analysis.

Dimensional variables	Symbol	Fundamental quantities		
		M	L	T
Length of the screen	l	0	1	0
Opening mesh size	L_T	0	1	0
Diameter of the cylinder	D	0	1	0
Acceleration of gravity	g	0	1	-2
Median diameter of agglomerates	d_{50}	0	1	0
Density of agglomerates	ρ	1	-3	0
Drum speed	N	0	0	-1
Angle of inclination	α	0	0	0
Feed rate	D_b	1	0	-1
Circularity	CIR	0	0	0
Apparent screening efficiency	ASE	0	0	0

Fig. 1. Schematic representation of the experimental rotating screen drum.

Fig. 2. Schematic representation of the specific method to quantify the screening efficiency of a rotary screen drum by using a matrix analysis.

CORRECTED GRAPHS

Fig. 3. Impact of the angle of inclination of the rotating screen drum on the screening efficiency parameters: apparent screening efficiency ($x_{11}+x_{22}+x_{33}$; O), global process efficiency (x_{22} ; ■), contamination rate of the collected product targets (y_{21} ; ×), and loss rate of the collected product targets (z_{32} ; Δ).

CORRECTED GRAPHS

Fig. 4. Impact of the angle of inclination of the rotating screen drum on the physicochemical characteristics (water content, compactness, and circularity) of the rolled agglomerated collected in the drawer 2.

CORRECTED GRAPHS

Fig. 5. Impact of the feed rate of the rotating screen drum on the screening efficiency parameters: apparent screening efficiency ($x_{11}+x_{22}+x_{33}$; ○), global process efficiency (x_{22} ; ■), contamination rate of the collected product targets (y_{21} ; ×), and loss rate of the collected product targets (z_{32} ; Δ).

CORRECTED GRAPHS

Fig. 6. Impact of the feed rate of the rotating screen drum on the physicochemical characteristics (water content, compactness, and circularity) of the rolled agglomerated collected in the drawer 2.

CORRECTED GRAPHS

Fig. 7. Impact of the drum rotational speed on the screening efficiency parameters: apparent screening efficiency ($x_{11}+x_{22}+x_{33}$; O), global process efficiency (x_{22} ; ■), contamination rate of the collected product targets (y_{21} ; ×), and loss rate of the collected product targets (z_{32} ; Δ).

CORRECTED GRAPHS

Fig. 8. Impact of the drum rotational speed, on the physicochemical characteristics (water content, compactness, and circularity) of the rolled agglomerated collected in the drawer 2.

CORRECTED GRAPHS

Fig. 9. Hydro-textural description (compactness vs. measured water content) of the small (○△), medium (●△), and large (●▲) wet agglomerates, before (△▲) and after (○●) processing inside the rotating screen drum. The saturation curve is dotted points.

CORRECTED GRAPHS

Fig. 10. Comparison of measured circularity (CIR) and apparent screening efficiency (ASE) with predicted values from Eq. (13) and Eq. (14).

Highlights

Screening efficiency of a rotating drum is measured by an original matrix analysis.

The rotating drum is very efficient to screen wet soft agglomerates of wheat.

The compactness and shape of the agglomerates are affected by the rolling process.

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